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PRODUCTION OF FORGED BERYLLIUM CONICAL STRUCTURAL SHAPES

Arthur F. Hayes
Ladish Co.

TECHNICAL REPORT AFML-TR-69-168

June 1969

Air Force Materials Laboratory
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio

NOTICES

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Arthur F. Hayes

FOREWORD

This Final Technical Report covers all the work performed under Contract AF33(615)-1396 from May 15, 1964 through February 12, 1969. The manuscript was released for publication by the author in June 1969.

This contract with Ladish Co. of Cudahy, Wisconsin, was initiated under Manufacturing Methods Project 8-247, "Production of Forged Beryllium Conical Structural Shapes." It has been accomplished under the technical direction of Mr. George Glenn of the Materials Processing Branch (MATP), Manufacturing Technology Division, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

Mr. Arthur F. Hayes of the Ladish Co. Metallurgical Department was the project engineer. Mr. R. P. Daykin, Assistant Vice-President for Research and Metallurgy directed the program effort, and Mr. Charles Burley, Jr., Director of Government Relations Division was in charge of contract administration and Government liaison.

This project was accomplished as part of the Air Force Manufacturing Methods Program, the primary objective of which is to implement, on a timely basis, manufacturing processes, techniques, and equipment for use in economical production of Air Force materials and components. The program encompasses the following technical areas:

Metallurgy	- Rolling, Forging, Extruding, Casting, Drawing, Powder, Metallurgy, Composites.
Chemical	- Propellants, Coatings, Ceramics, Graphites, Nonmetallics.
Electronic	- Solid State, Materials & Special Techniques, Thermionics.
Fabrication	- Forming, Material Removal, Joining, Components.

Suggestions concerning additional Manufacturing Methods required on this or other subjects will be appreciated.

This Technical Report has been reviewed and is approved.

H. A. Johnson

H. A. JOHNSON, CHIEF
MATERIALS PROCESSING BRANCH
MANUFACTURING TECHNOLOGY DIVISION

ABSTRACT

This manufacturing program, originally initiated for forging beryllium jet engine blades and discs and later redirected to beryllium cones, established an improved beryllium forging grade and a practical forging sequence for the manufacture of cones having height/diameter ratios greater than 1.5-to-one and nominal yield strength of 75 Ksi. Of the four types of beryllium selected for evaluation during Phase I, the grade hot-pressed from minus 20 micron virgin powder reproducibly demonstrated superior forgeability and mechanical properties. All grades showed higher forgeability at 1300-1350°F versus 1350-1450°F. Material, tooling, and technical development for the blade forgings were transferred to a similar, more comprehensive, beryllium engine program.

A series of cones 8-1/4-inch major diameter was produced and evaluated during Phase III by a basic manufacturing process consisting of forging a conical frustum from a hollow cylinder. Expendable hot filler material such as graphite or brass were used to prevent buckling and to optimize material utilization. A different deformation processing sequence was used on each cylindrical cone blank to produce various textures and a range of mechanical property values for future selection of the most economical process capable of meeting specific requirements. Forging defects developed during extrusion of the hollow cylinders so that an adequate evaluation of the forming process was not possible in Phase III. Tensile data showed yield strengths from 78 to 96 Ksi and ultimate strengths from 90 to 123 Ksi for circumferential and axial test directions. Tensile elongation varied considerably, depending upon forging sequence and testing location and direction.

The program was modified to provide additional subscale trials and to change configuration of the full-scale cone to more closely approximate future requirements. These trials were directed toward defining parameters such as the degree of restraint and evaluating methods of maintaining geometry control. The conical frustums formed successfully, showing that open-ended cylinders can be formed without using forward restraint. Both graphite and brass fillers effectively maintained wall thickness. The procedure for manufacturing the full-scale cone entailed back-extrusion, forward-extrusion, and forming. Rupturing occurred during both extrusion operations and prevented progressing to the forming operation. Additional trials should correct these technical difficulties and enable production of forged beryllium cones in the size range of 14-inch-diameter by 48 inches high having nominal yield strength of 75 Ksi.

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I. INTRODUCTION

A. Program Objective

The original objective of this program was to develop and evaluate closed-die forging and extrusion techniques for producing high-strength beryllium forgings with optimized multidirectional properties for application in advanced-design jet engine compressor blades and discs. During the course of the program performance, however, it was deemed advisable to redirect this project from engine hardware to aerospace structural applications. The need for a more comprehensive engine program was foreseen and initiated, using the technology, material grade, and a portion of the tooling developed in this program. Duplication of effort was thereby eliminated and the opportunity was provided to investigate another prime area of interest, namely, beryllium conical forgings. This latter objective was subsequently refined by redirecting the program to conical frustums having height/diameter ratios greater than three-to-one.

B. Program Approach

Manufacturing technology for forged beryllium jet engine components was to be developed during this program using the following sequence:

1. Select the optimum grade of beryllium which could be produced in commercial quantities.
2. Forge the beryllium billets in a manner which was designed to enhance the mechanical properties.
3. Forge to refine the contour.
4. Demonstrate reproducibility of the entire manufacturing process.

The objective of Phase I was to select and establish a grade of vacuum-hot-pressed beryllium which demonstrates the best capabilities for fulfilling the goals of this program. Activity included evaluation of four types of beryllium material and selection of the most satisfactory grade for use in subsequent phases. High-strength, fine-grained beryllium is a new material designed to meet anticipated requirements for jet engine and aerospace structural applications. The development of new materials always entails direction of effort toward many different, though interrelated, problems including commercial feasibility of manufacture, evaluation of material characteristics, fabricability, market potential and requirements, and cost.

During our many years of experience in forging beryllium, Ladish Co. developed familiarity with its characteristics, the problems associated with component manufacture, application requirements, and billet material manufacture. The selection of the program materials to be evaluated was based upon a logical analysis of attributes aimed at imparting a greater degree of reliability, strength, and toughness to forged beryllium structures.

Brittleness can be aggravated by non-uniformity within a material. Intermetallics and other refractory materials are generally known for their brittle behavior. Thus, the size and quantity of non-metallic inclusions was minimized in an attempt to develop a tougher grade of beryllium. All grades investigated were produced from minus 20 micron powder to help reduce the size of nonmetallic inclusions, and thereby restrict the occurrence of crack nucleation and propagation through or around an inclusion.

Wrought, fine-grained beryllium also has a history of high strength and good tensile ductility in selected directions. In order to improve reproducibility and reduce impurity content, two of the beryllium grades (Types 2 and 3) were vacuum remelted beryllium and one grade (Type 4) was vacuum melted virgin beryllium. In addition, the minus-five-micron particle size fraction from Types 1 and 2 beryllium was eliminated to further control impurities. It was known that the oxide content of the fines was significantly higher than that of the larger-size powder fractions. Other impurities, of a type more friable than beryllium, were expected to be present in higher quantity in the fines.

The evaluation was based upon response to forging and resultant mechanical properties. Type 4 beryllium, which was hot-pressed from minus 20 micron virgin powder, reproducibly demonstrated superior forgeability and mechanical properties.

Phase II blade manufacture was to utilize several forging operations to work the beryllium in three directions to promote increased strength and ductility in all directions. A final forging operation was to improve contour refinement. The finished blade for Phase II was designed to permit extensive mechanical property testing, and, as such, was not intended to be machined into blade hardware. However, the degrees of reduction imparted during the various operations in Phase II were to remain essentially the same for blades manufactured during Phase III, unless tests showed that a modified procedure would offer greater advantages.

Experience in forging beryllium showed that significant mechanical property improvement could be attained for dimensional reductions of 60 per cent or greater. Multidirectional forging programs at Ladish Co. indicated that a balance in crystallographic orientation between the three principal directions could be approached by using decreasing degrees of reduction. Reductions of four-to-one, three-to-one, and 2.5-to-one were selected for billet extrusion, upset-forging, and blade extrusion operations, respectively. It was anticipated that the blade extrusion would establish a degree of preferred orientation along the longitudinal-long transverse plane of the airfoil section. This becomes necessary to introduce a degree of contour refinement. The degree of preferred orientation present was to be measured and the effects of this orientation would be reflected in the mechanical property data determined. Minor adjustments in the reduction ratios selected could be made at that time if engine design requirements so dictated.

During the performance of Phase II, it was necessary to redirect this program as indicated earlier. Therefore, the program objective was shifted toward development of an optimum processing sequence for large, conical beryllium configurations for aerospace structural application. A survey of hardware requirements was conducted to select a structural part which would most significantly advance the state-of-the-art for forged beryllium. A conical shape was selected because it represented the geometry of greatest interest for forged beryllium aerospace applications and one which required substantial development. Specific emphasis was aimed at the production of large, conical beryllium shapes possessing properties beyond those achievable through vacuum-hot-pressing of commercially available beryllium powder.

The manufacture of such a conical beryllium forging required substantial amounts of money for input material, tooling, and forging development effort. The risk factor was unknown because a forging operation had not been developed to produce the final conical configuration, and a manufacturing sequence that would produce the required mechanical property level had also not been developed. The development effort was technically feasible because desirable property levels had been obtained in smaller forgings of other geometries. Experience showed that beryllium must be forged using compressive restraint to prevent cracking or rupturing. Hydrodynamic compressive forging techniques could be adapted to the conical configuration when it is formed from a hollow, cylindrical preform shape. Forming offers advantages over back-extruding the conical shape directly. The high tooling pressures generated during the back-extrusion operation are significantly reduced in the forming operation. Further, back-extrusion is limited to conical parts having a height/diameter ratio of approximately one-to-one, due to tooling limitations. Forming can far exceed this level.

The development of a processing sequence for a large beryllium conical shape was planned for two steps. The configuration for the first step was subscale to conserve costly material. The objectives of this portion of the program were:

1. To develop the forging parameters necessary for reproducibly and reliably forming the selected conical shape; and

2. To evaluate the effects of ten forging sequences using different reductions and combinations of forging operations upon the metallurgical and mechanical properties of the forged, subscale beryllium conical shape.

On the basis of results obtained in this subscale investigation, the most favorable forging sequence was chosen to manufacture a full-scale beryllium conical forging. The objective of this part of the program was to evaluate the effects of the increase in mass upon the manufacturing methods, metallurgical, and mechanical properties of the forged, conical beryllium configuration.

II. MATERIAL EVALUATION

A. Description of Beryllium Material

Five eight-inch-diameter by five-inch-high beryllium billets were vacuum-hot-pressed by The Brush Beryllium Company at Elmore, Ohio, using the types of powders defined below:

Type 1 -- Minus 20 micron recycle powder with the minus five micron fraction removed.

Type 2 -- Minus 20 micron remelt virgin powder with the minus five micron fraction removed.

Type 3 -- Minus 20 micron remelt virgin powder.

Type 4 -- Minus 20 micron virgin powder.

The material identity, chemistry, vacuum-hot-pressing parameters, powder size distribution, and mechanical properties of the vacuum-hot-pressed block are presented in Tables I through IV. Data in Tables I and II were provided by The Brush Beryllium Company. The overall degree of purity of the four types of beryllium is shown to be similar with the exception of beryllium oxide, BeO. A noticeable increase in purity as a result of removing the minus five micron powder fraction is demonstrated by comparing Types 2 and 3 beryllium materials in Table I. The powder size analysis shown in Table II indicates that the Type 4 beryllium has a slightly higher percentage of plus 20 micron powder particles than that of the other beryllium types. The mechanical properties of the vacuum-hot-pressed blocks presented in Table III show relatively good strengths and ductilities for all types investigated. Type 4 material demonstrated the most uniform strength between the two directions tested. A decrease in ductility and strength in the transverse direction existed for all billets.

The five billets were inspected for soundness using dye-penetrant, macroetch, X-ray, and ultrasonic inspection techniques, and were found to be free of flaws detectable through use of these methods.

All billets were examined metallographically to determine uniformity of structure within a billet and to compare the microstructures of the different heats. Typical structures of the five heats are shown in Figures 1 through 5 at 500X magnification using polarized light. The specimens were then etched and re-examined at 500X using the optical microscope and at 1500X using the electron microscope. Typical structures of the five heats after etching are shown in Figures 6 through 15. The degree of uniformity between top, middle, and bottom positions is shown for all the heats in Figures 6 through 10.

TABLE I

DESCRIPTION OF BERYLLIUM BILLETS FOR MATERIALS EVALUATION

Element	Type 1 Heat No. 3362	Type 2 Heat No. 3258	Type 3 Heat No. 3259	Type 4 Heat No. 3363	Type 4 Heat No. 3364
Be (per cent)	97.1	98.35	98.3	98.86	98.87
BeO (per cent)	3.26	2.15	2.30	1.90	1.99
C (per cent)	0.095	0.072	0.15	0.104	0.078
Al (ppm)*	400	550	700	350	500
Cr (ppm)	70	90	160	150	140
Fe (ppm)	1256	1126	1070	934	950
Mg (ppm)	40	110	350	30	30
Mn (ppm)	81	85	70	60	56
Ni (ppm)	180	120	160	120	110
Ti (ppm)	200	230	480	320	330
Ag (ppm)	6	3	4	5	4
Ca (ppm)	<100	<85	<85	<85	<85
Co (ppm)	5	5	5	3	3
Cu (ppm)	140	50	90	90	50
Mo (ppm)	<20	<8	10	<8	<8
Pb (ppm)	<10	<6	8	8	<6
Si (ppm)	350	280	600	120	220
Zn (ppm)	<100	<55	<55	<55	<55
N (ppm)	228	146	355	214	220
Pressing Temperature (°C)	1095	1080	1100	1080	1100
Pressure (psi)	2000	2000	2000	2000	2000

* ppm = parts per million.

TABLE II

POWDER PARTICLE SIZE ANALYSIS OF BERYLLIUM BILLETS FOR MATERIALS EVALUATION

Micro-Sieve Size Fraction (microns)	Type 1 Heat No. 3362 (per cent)	Type 2 Heat No. 3258 (per cent)	Type 3 Heat No. 3259 (per cent)	Type 4 Heat No. 3363 (per cent)	Type 4 Heat No. 3364 (per cent)
Minus 5	0.4	1.1	19.2	15.5	16.8
Minus 10	24.4	31.9	60.0	55.6	52.3
Minus 15	62.5	69.4	83.3	76.5	77.8
Minus 20	91.3	91.7	96.5	89.6	89.4
Minus 25	99.1	98.0	98.7	95.9	96.4
Minus 30	100.0	98.1	99.2	98.3	98.0
Minus 35	100.0	98.2	99.2	99.0	98.7
Minus 40	100.0		99.4		
Minus 45	100.0	99.2		100.0	99.3
Minus 60	100.0	99.3	99.5	100.0	99.5
Minus 75	100.0	99.4	99.6	100.0	99.6

TABLE III

MECHANICAL PROPERTIES OF AS-HOT-PRESSED BERYLLIUM BILLETS FOR MATERIALS EVALUATION

Type	Heat No.	Direction of Test	Yield Strength (Ksi)	Ultimate Strength (Ksi)	Elongation (per cent)	Reduction of Area (per cent)
1	3362	Circumferential	51.8	72.6	4	6
		Circumferential	52.6	71.8	3	5
		Axial	49.8	61.7	1 *	2 *
		Axial	47.6	67.1	3	4
2	3258	Circumferential	54.7	75.2	4	7
		Circumferential	49.6	72.2	7	7
		Axial	45.3	62.7	3	4
		Axial	49.1	61.0	1	2
3	3259	Circumferential	44.5	71.2	6	7
		Circumferential	48.6	73.0	4	5
		Axial	42.3	61.9	2	3
		Axial	50.6	64.3	2	2
4	3363	Circumferential	51.2	73.7	4	5
		Circumferential	54.2	76.4	5	7
		Axial	52.1	68.3	2	2
		Axial	51.4	69.1	1	2
4	3364	Circumferential	53.2	76.8	4	7
		Circumferential	51.0	75.1	6	6
		Axial	50.9	68.6	2	2
		Axial	50.9	66.5	1	2

* Invalid Test - Specimen failed through threads.

TABLE IV

IMPACT PROPERTIES OF AS-HOT-PRESSED BERYLLIUM BILLETS FOR MATERIALS EVALUATION

Type	Heat No.	Direction of Test	Impact Strength (ft-lbs.)	
			Unnotched Specimen	Notched Specimen
1	3362	Circumferential	4.8	0.19
		Circumferential	8.6	0.30
		Axial	1.8	0.2
		Axial	1.2	0.19
2	3258	Circumferential	10.4	0.28
		Circumferential	12.9	0.19
		Axial	3.7	0.19
		Axial	4.7	0.21
3	3259	Circumferential	10.2	0.41
		Circumferential	11.3	0.51
		Axial	4.7	0.23
		Axial	1.8	*
4	3363	Circumferential	10.1	0.23
		Circumferential	10.5	0.21
		Axial	2.1	0.21
		Axial	2.8	0.30
4	3364	Circumferential	14.1	0.21
		Circumferential	11.4	0.23
		Axial	3.8	0.19
		Axial	4.2	0.21

* Specimen cracked during machining.

FIGURE 1

MICROSTRUCTURE OF VACUUM HOT-PRESSED BERYLLIUM
Heat No. 3362, Type 1 Material, Unetched,
Polarized Light, 500X Magnification

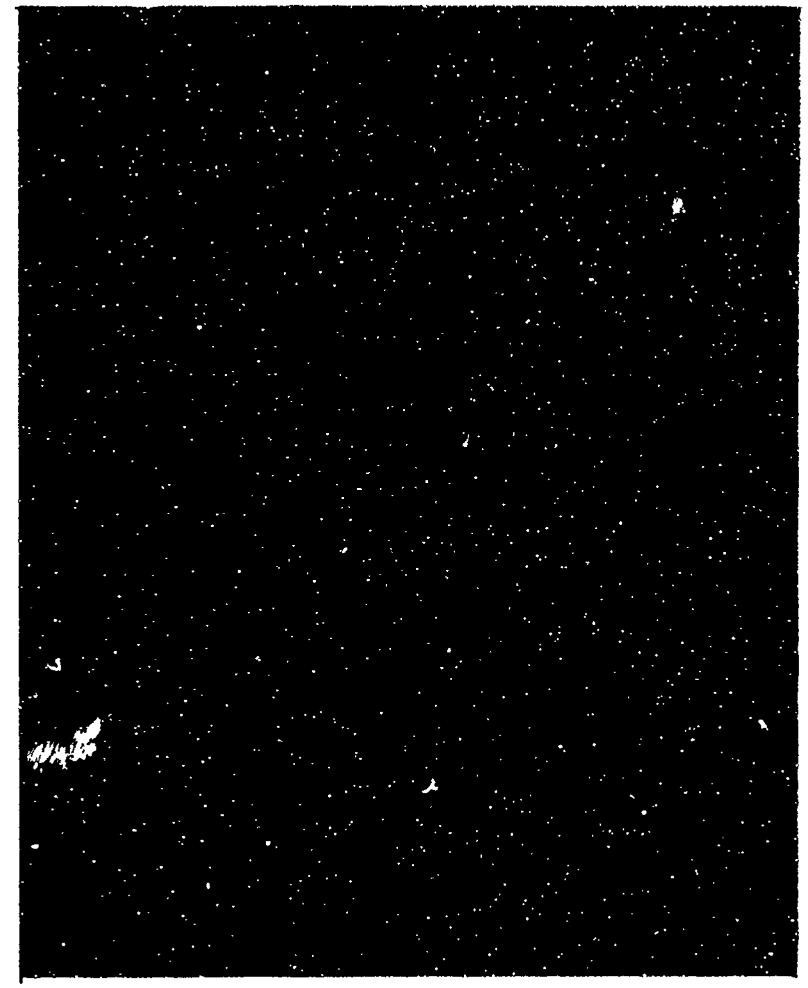


FIGURE 2

MICROSTRUCTURE OF VACUUM HOT-PRESSED BERYLLIUM
Heat No. 3258, Type 2 Material, Unetched,
Polarized Light, 500X Magnification

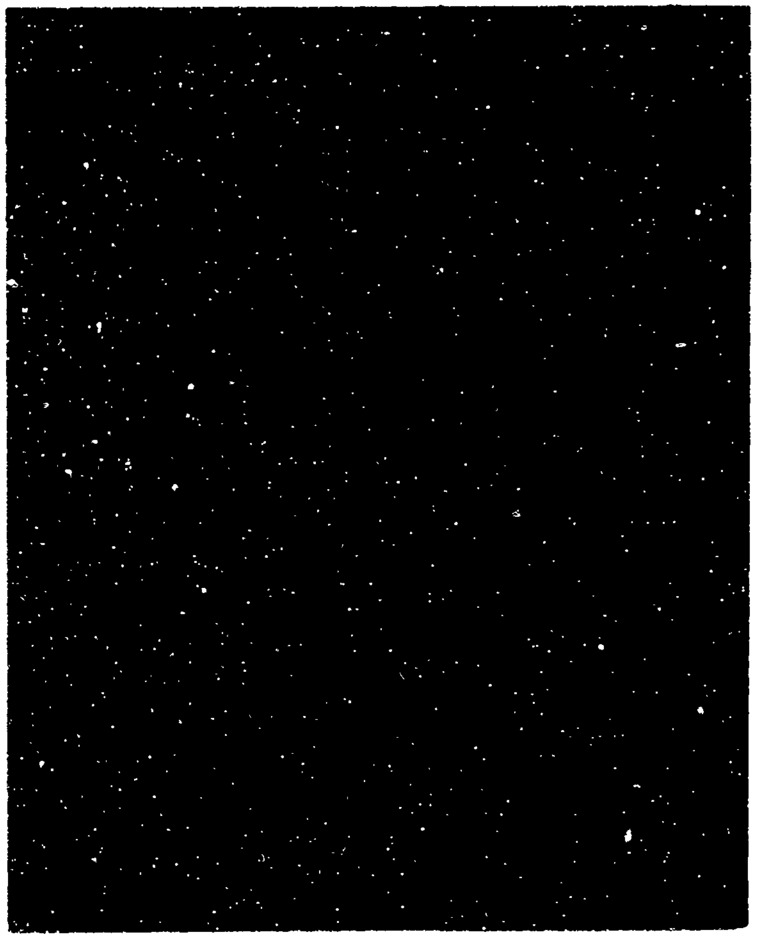


FIGURE 3

MICROSTRUCTURE OF VACUUM HOT-PRESSED BERYLLIUM
Heat No. 3259, Type 3 Material, Unetched,
Polarized Light, 500X Magnification

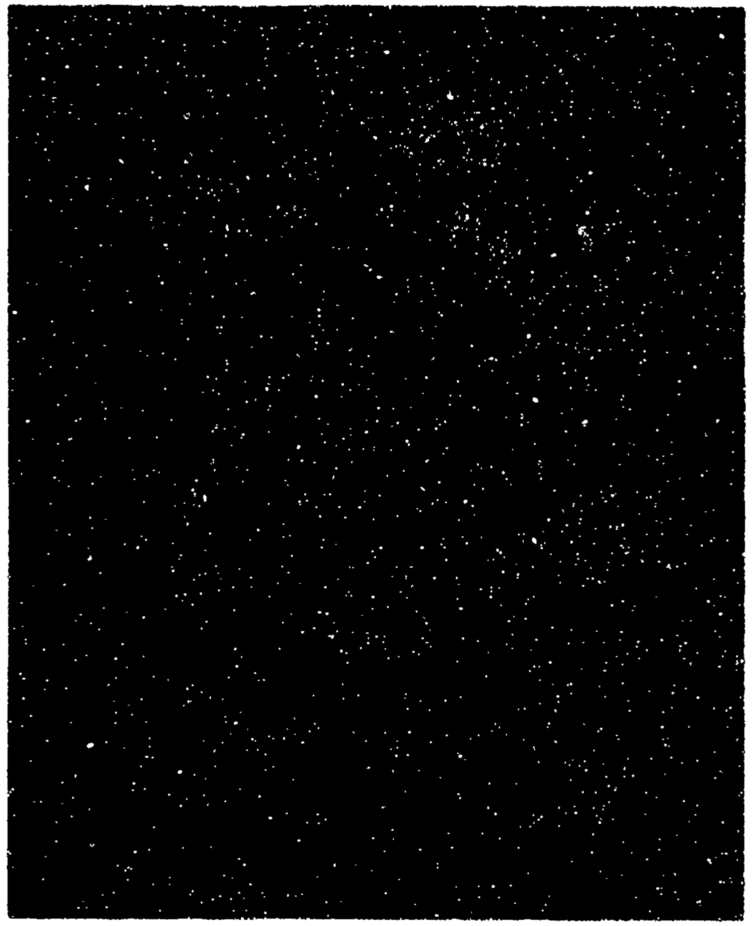


FIGURE 4

MICROSTRUCTURE OF VACUUM HOT-PRESSED BERYLLIUM
Heat No. 3363, Type 4 Material, Unetched,
Polarized Light, 500X Magnification

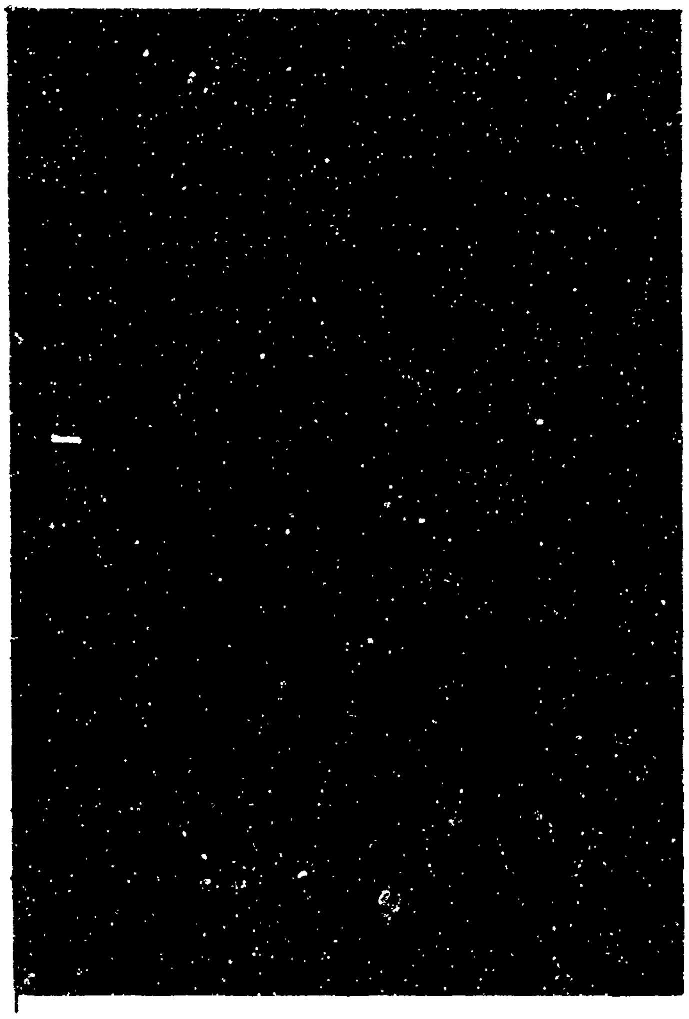
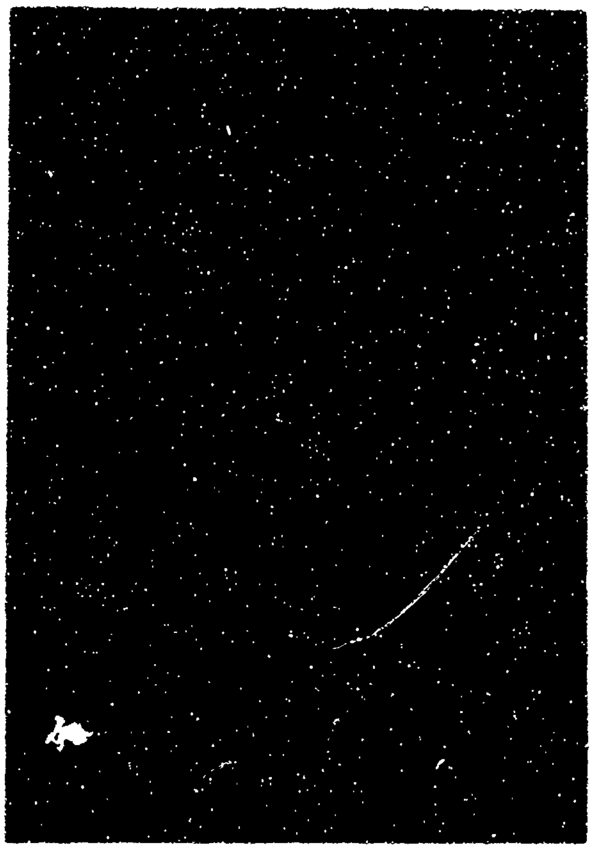
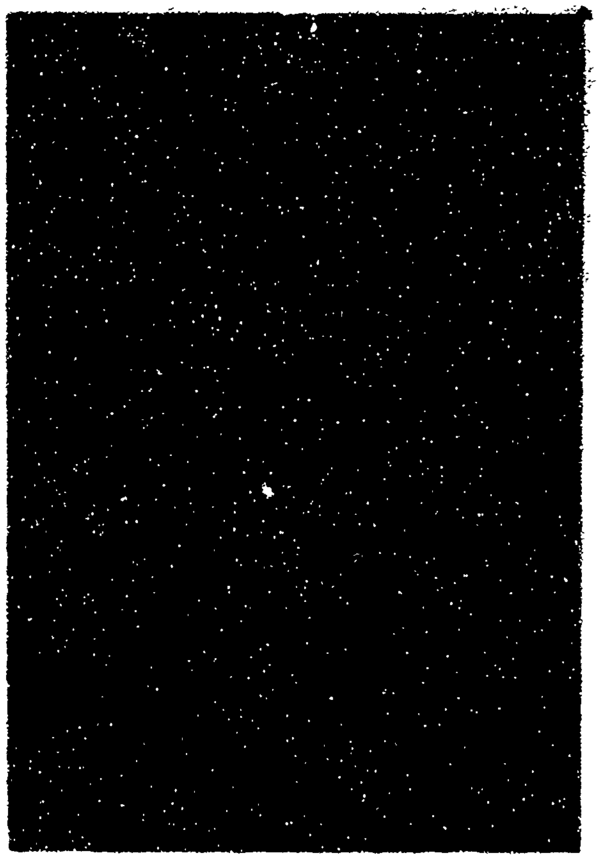


FIGURE 5

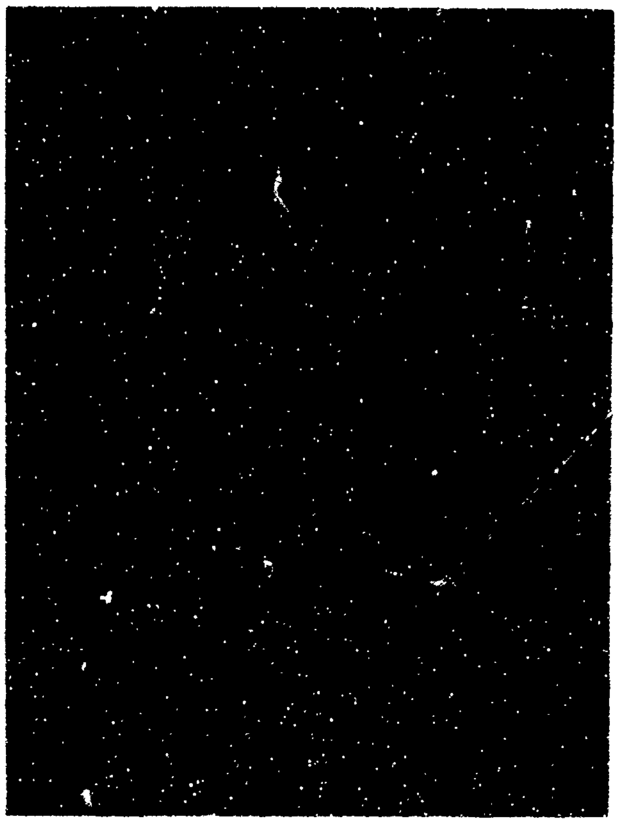
MICROSTRUCTURE OF VACUUM HOT-PRESSED BERYLLIUM
Heat No. 3364, Type 4 Material, Unetched,
Polarized Light, 500X Magnification



Top Outer Diameter



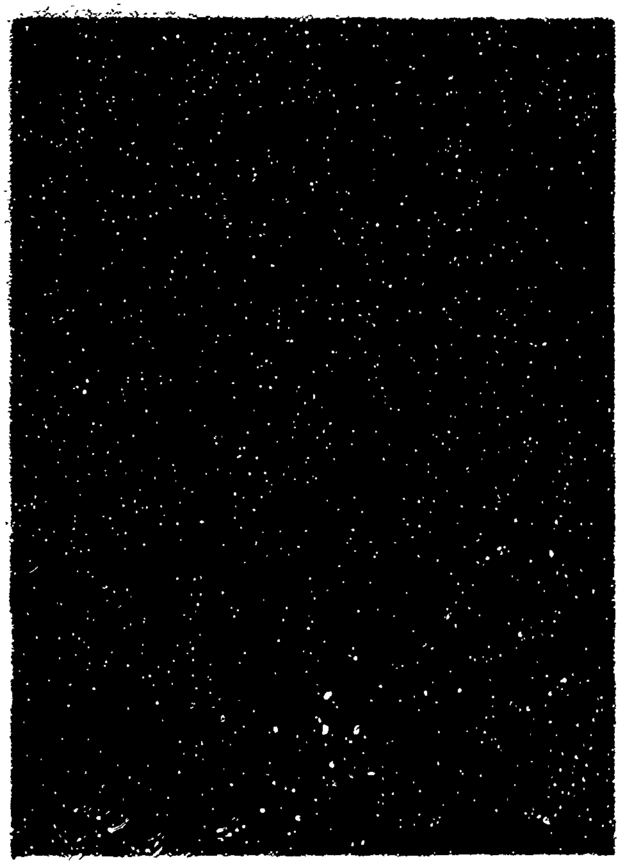
Mid-height Outer Diameter



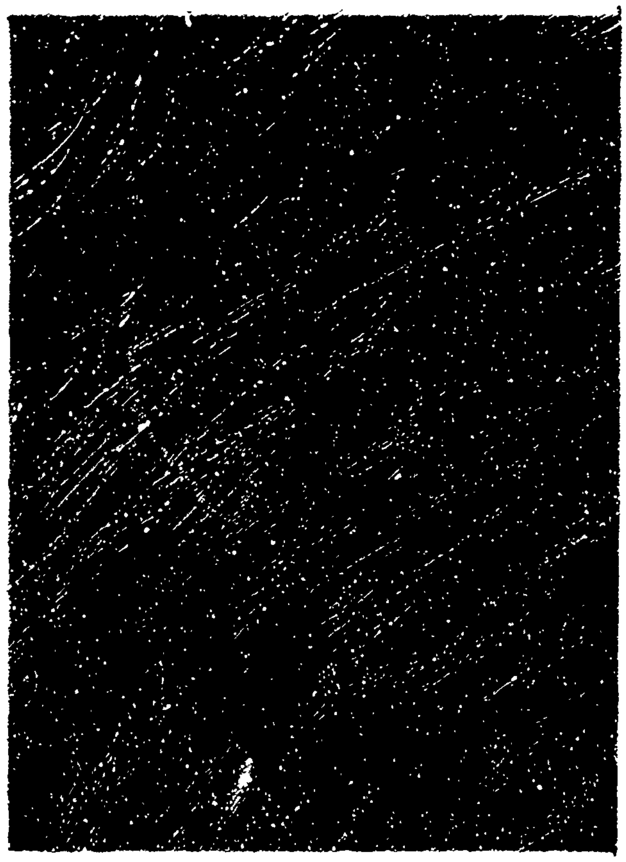
Bottom Outer Diameter

FIGURE 6

MICROSTRUCTURE OF VACUUM HOT-PRESSED BERYLLIUM
Heat No. 3362, Type 1 Material, Etched, 500X
Magnification, Three Locations



Top Outer Diameter

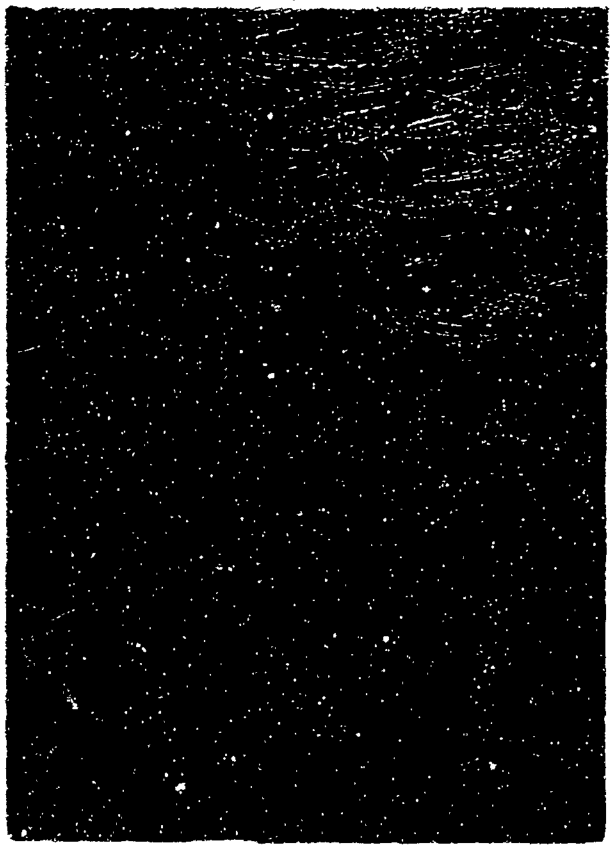


Mid-height Outer Diameter

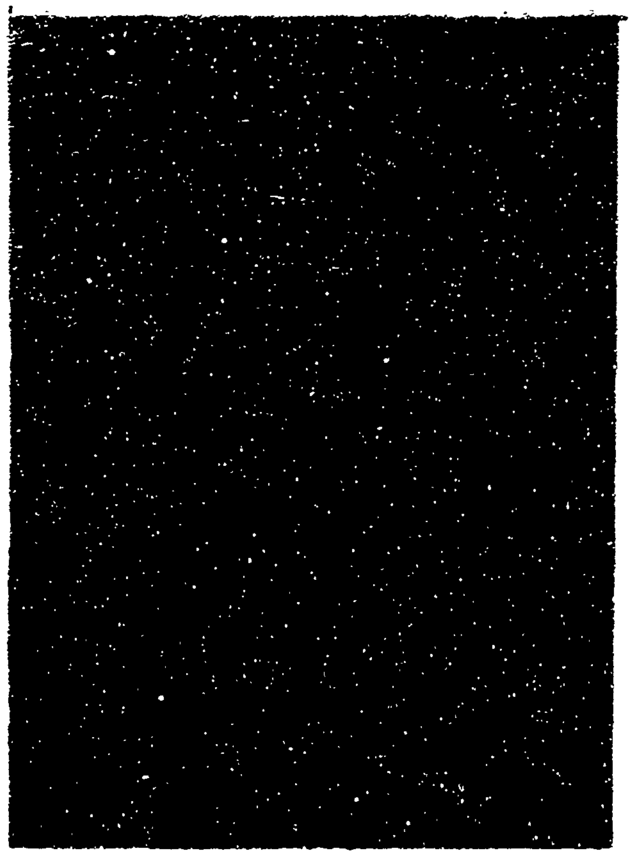
Bottom Outer Diameter

FIGURE 7

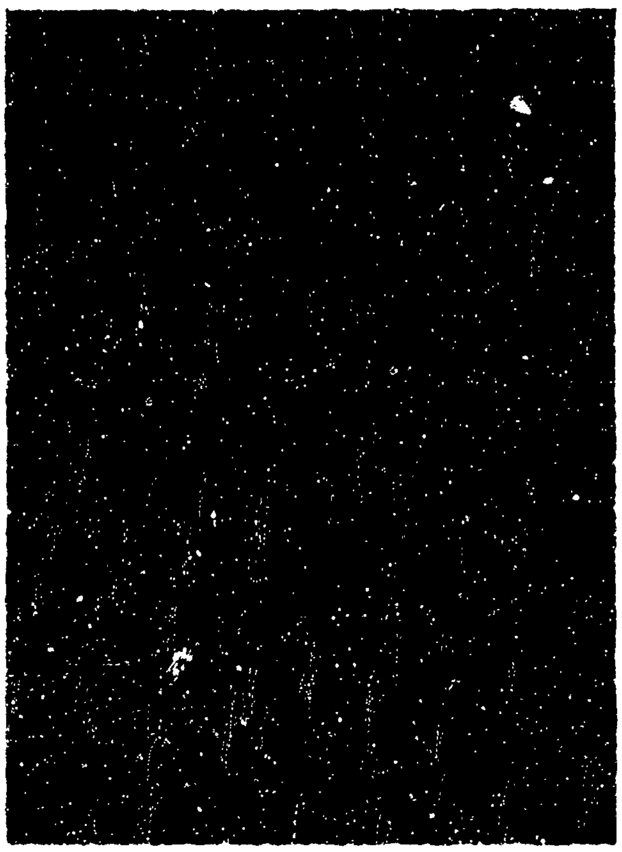
MICROSTRUCTURE OF VACUUM HOT-PRESSED BERYLLIUM
Heat No. 3258, Type 2 Material, Etched, 500X
Magnification, Three Locations



Top Outer Diameter



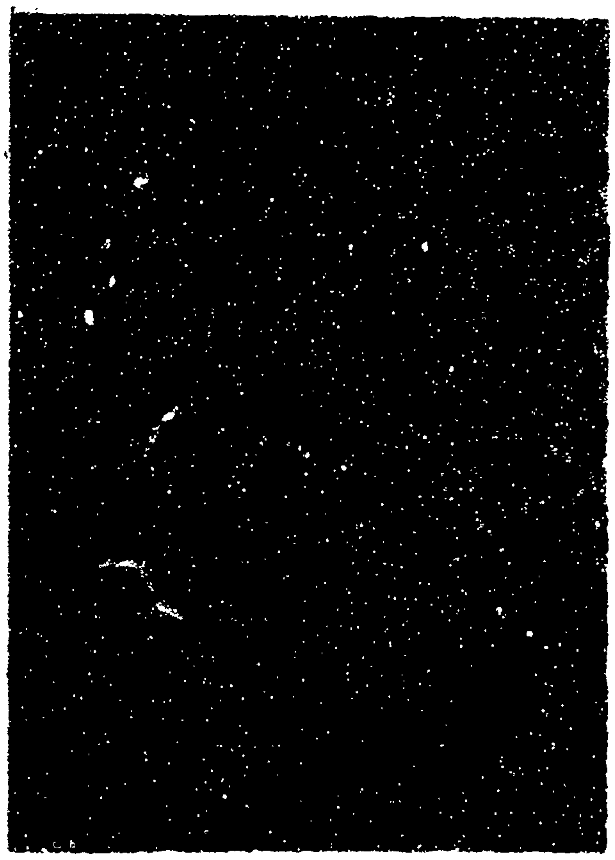
Mid-height Outer Diameter



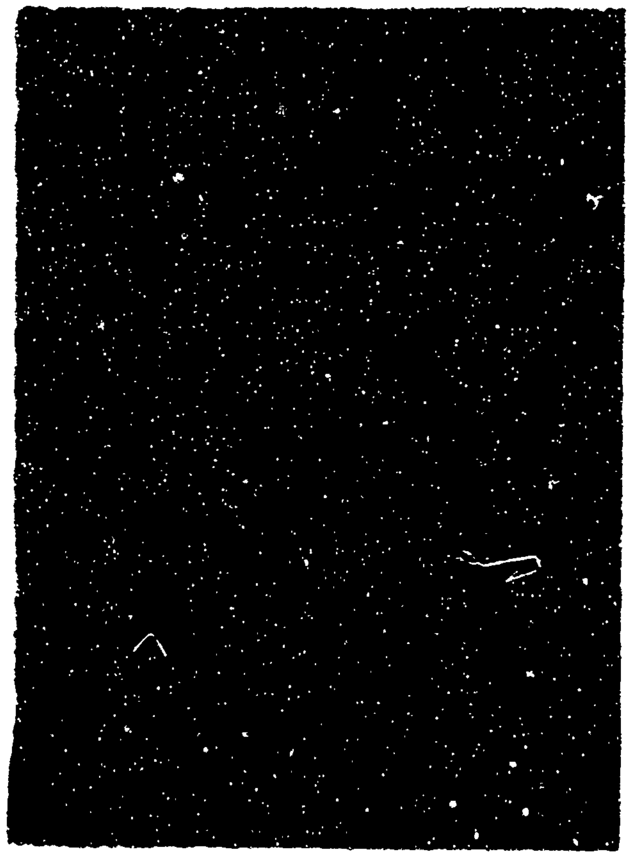
Bottom Outer Diameter

FIGURE 8

MICROSTRUCTURE OF VACUUM HOT-PRESSED BERYLLIUM
Heat No. 3259, Type 3 Material, Etched, 500X Magnification, Three Locations



Top Outer Diameter

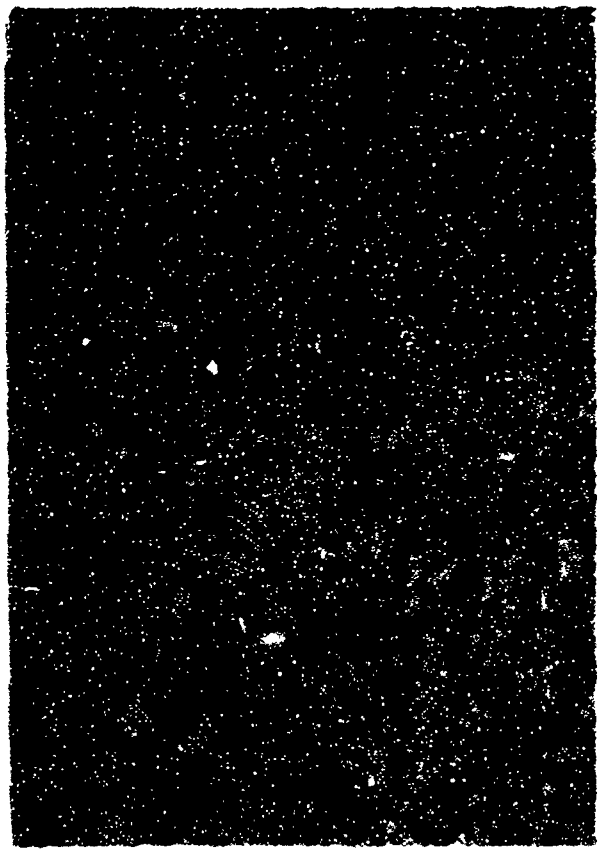


Mid-height Outer Diameter

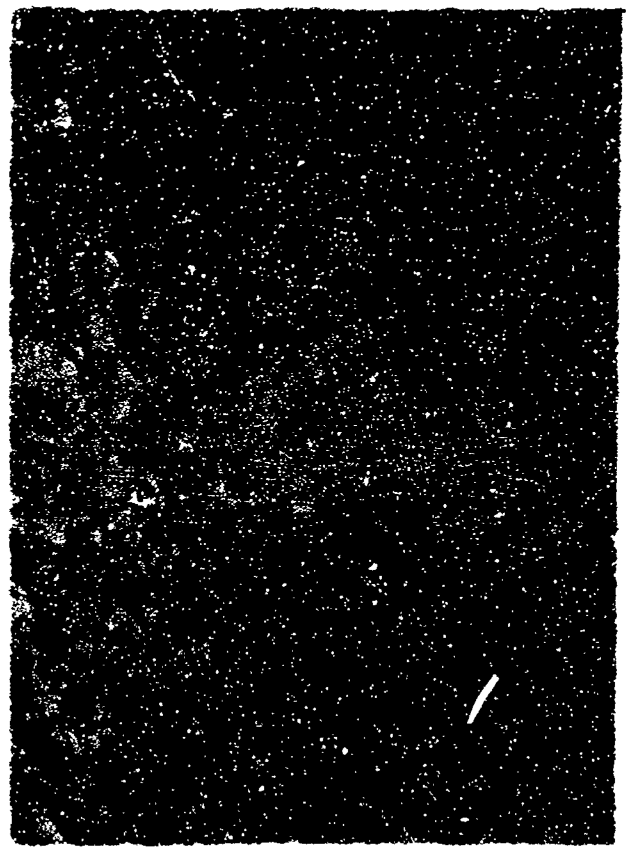
Bottom Outer Diameter

FIGURE 9

MICROSTRUCTURE OF VACUUM HOT-PRESSED BERYLLIUM
Heat No. 3363, Type 4 Material, Etched, 500X
Magnification, Three Locations



Top Outer Diameter



Mid-height Outer Diameter

Bottom Outer Diameter

FIGURE 10

MICROSTRUCTURE OF VACUUM HOT-PRESSED BERYLLIUM
Heat No. 5364 Type 4 Material, Etched, 500X
Magnification, Three Locations

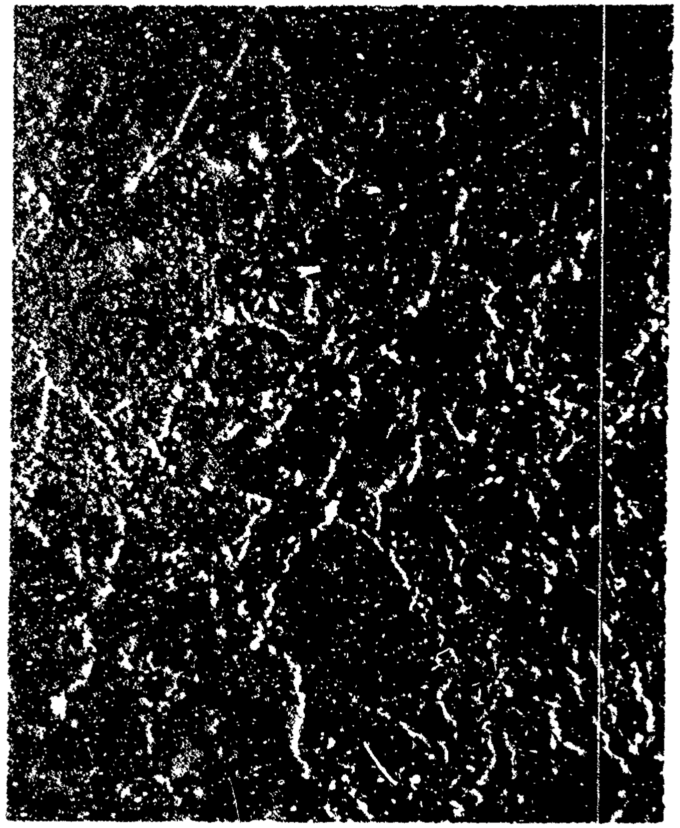


FIGURE 11

(Refer to Figure 6)

MICROSTRUCTURE OF VACUUM HOT-PRESSED BERYLLIUM
Heat No. 3362, Top Outer Diameter, Etched,
1500X Magnification, Electron Microscope

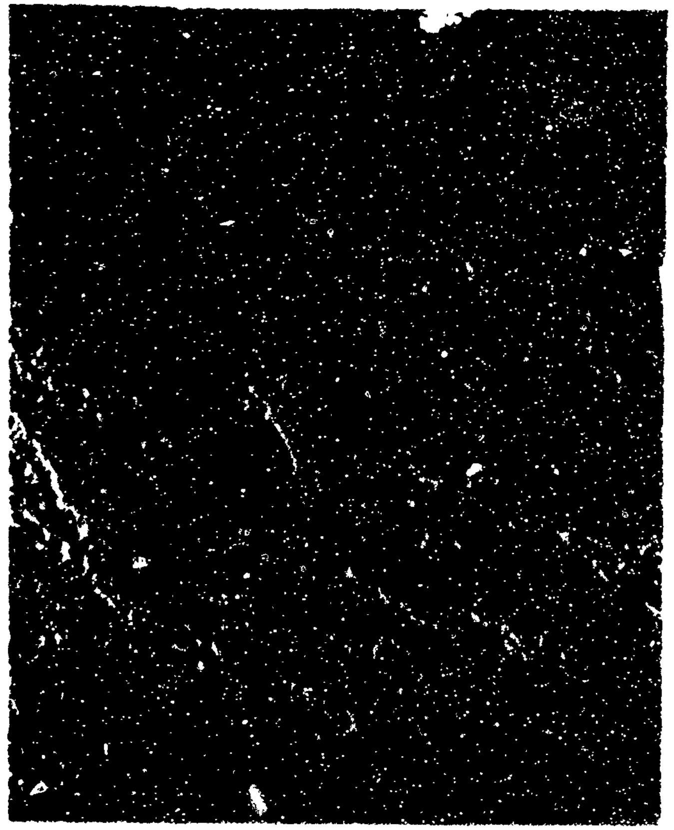


FIGURE 12

(Refer to Figure 7)

MICROSTRUCTURE OF VACUUM HOT-PRESSED BERYLLIUM
Heat No. 3258, Top Outer Diameter, Etched,
1500X Magnification, Electron Microscope

FIGURE 13

(Refer to Figure 8)

MICROSTRUCTURE OF VACUUM HOT-PRESSED BERYLLIUM
Heat No. 3259, Top Outer Diameter, Etched,
1500X Magnification, Electron Microscope

FIGURE 14

(Refer to Figure 9)

MICROSTRUCTURE OF VACUUM HOT-PRESSED BERYLLIUM
Heat No. 3363, Top Outer Diameter, Etched,
1500X Magnification, Electron Microscope

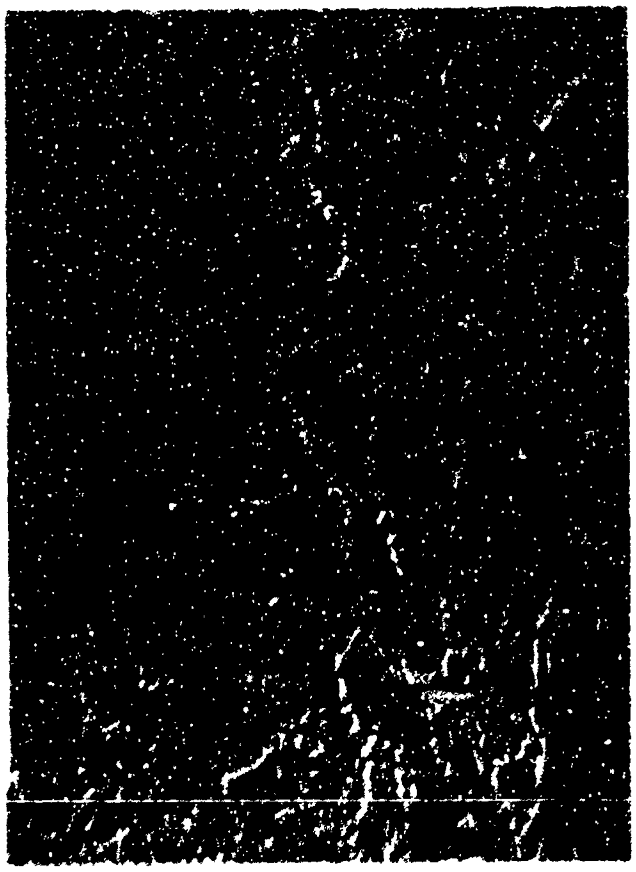


FIGURE 15

(Refer to Figure 10)

MICROSTRUCTURE OF VACUUM HOT-PRESSED BERYLLIUM
Heat No. 3364, Top Outer Diameter, Etched,
1500X Magnification, Electron Microscope

B. Forgeability Tryouts

The five beryllium billets evaluated were sectioned and machined into test specimens as shown in Figure 16. The two-inch-diameter by two-inch-high and the five-inch-diameter by five-inch-high forgeability samples were upset-forged as shown in the temperature and time schedule in Table V. Variables investigated included forging temperature, time at forging temperature, effect of billet position, reproducibility, effect of test specimen size, and material. Tests were conducted on a 3000-ton hydraulic press, which has adequate power for forging the larger-size specimens. The samples were heated in an electric furnace to the required forging temperature, held at temperature for the specified time, and upset-forged to a 60 per cent reduction in height between dies heated to 800°F±50°. The forging dies were lubricated with a graphite-in-oil lubricant prior to forging. All specimens were stress-relieved at 1400°F for one-half hour and slow cooled in Sil-O-Cel after forging. After cooling to room temperature, the samples were cleaned by vapor-blasting and machined to determine the forgeability index. The largest possible defect-free disc was machined from each upset specimen and inspected for flaws using etch and dye-penetrant techniques. The ratio of the weights of the forged disc before and after machining determined the forgeability index number.

The as-forged-and-cleaned specimens are shown in the photographs in Figures 17, 18, and 19. The forgeability results are presented in Table VI and are identified with the corresponding thermal treatment. The results show that Type 4 material is reproducibly superior to the other types tested. Only one low result (55.2 per cent) occurred for Type 4 material. The duplicate sample adjacent to this position which was forged at the same temperature attained a 74.6 per cent forgeability index rating. The difference in results may be due to a variation in strain rate during forging, which will be discussed later.

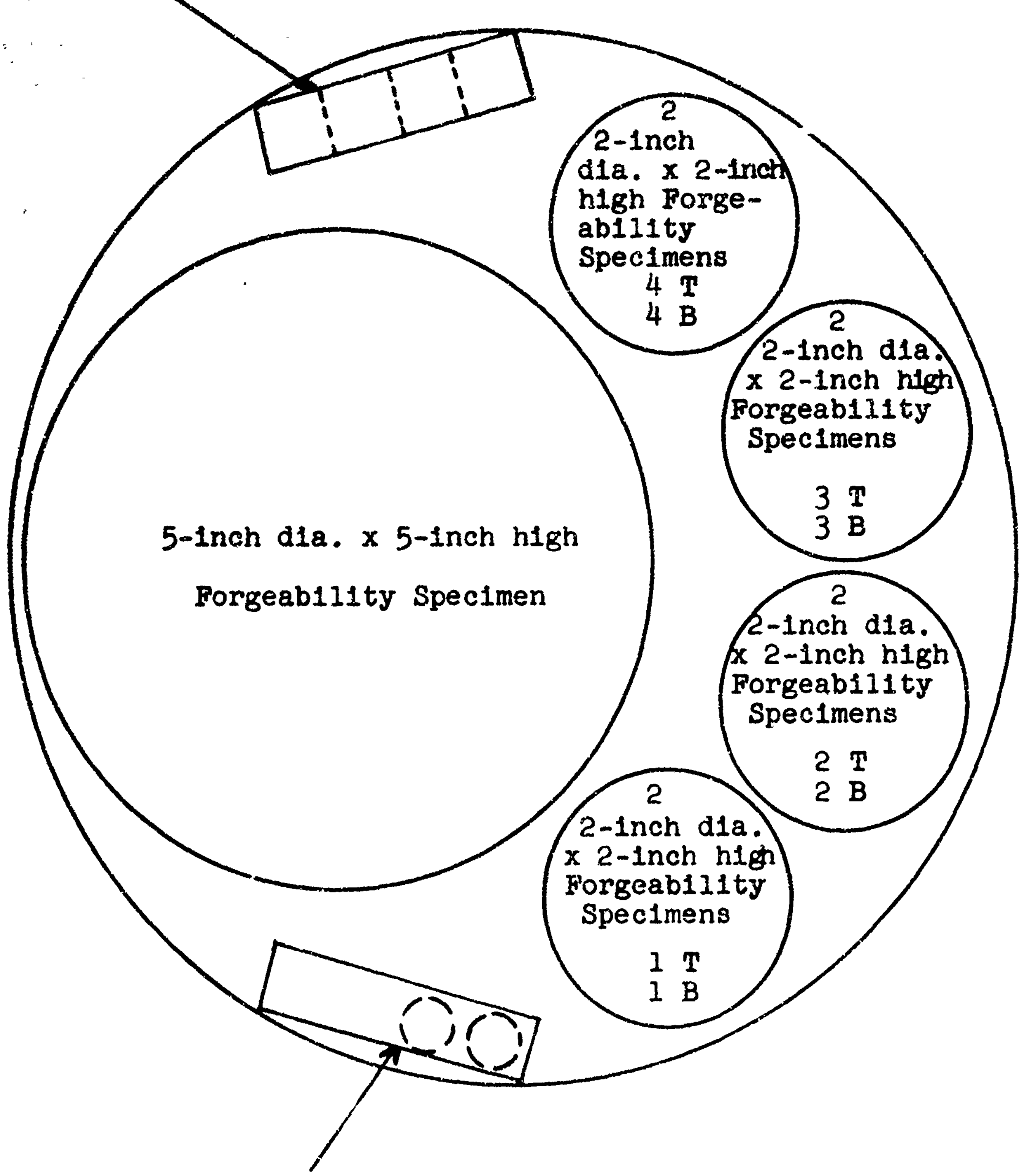
The upset-forged samples were tested for tensile and impact properties. Tensile specimen dimensions were 0.125-inch-diameter by 0.500-inch gage length with 1/4-inch threaded ends. Unnotched Charpy impact specimen dimensions were the standard ten by ten by 55 millimeters. A two-millimeter-deep notch with a root radius of 0.010 inch was machined into the notched impact specimens. Test results are shown in Tables VII through XI.

Typical microstructures in the etched condition at 500X magnification are shown in the photomicrographs in Figures 20 through 24 for samples given the one-hour-at-1400°F pre-forging thermal cycle. The microstructure of the bottom forgeability specimen of this series is also shown at 1500X magnification using the electron microscope.

Legend: **T = Top of vacuum hot pressed block.**
B = Bottom of vacuum hot pressed block.

Scale: **Three-fourths**

4 Circumferential Charpy Specimens
4 Axial Charpy Specimens



2 Circumferential Tensile Specimens (0.125-inch dia.)
2 Axial Tensile Specimens (0.125-inch dia.)

FIGURE 16

TEST PLAN FOR PHASE I BILLET MATERIAL EVALUATION

TABLE V

FORGEABILITY SCHEDULE OF VARIABLES INVESTIGATED

Material Type	Heat No.	Billet Size (inches)	Billet Position	Heating Temperature (°F)	Time at Temperature (Hours)
1	3362	2 Dia. x 2	Bottom	1300	1.0
		2 Dia. x 2	Bottom	1350	1.0
		2 Dia. x 2	Bottom	1400	1.0
		2 Dia. x 2	Top	1400	1.0
		2 Dia. x 2	Top	1400	1.0
		2 Dia. x 2	Bottom	1450	1.0
		2 Dia. x 2	Top	1400	0.5
		2 Dia. x 2	Top	1400	2.5
		5 Dia. x 5	--	1400	1.0
2	3358	2 Dia. x 2	Bottom	1300	1.0
		2 Dia. x 2	Bottom	1350	1.0
		2 Dia. x 2	Bottom	1400	1.0
		2 Dia. x 2	Top	1400	1.0
		2 Dia. x 2	Top	1400	1.0
		2 Dia. x 2	Bottom	1450	1.0
		2 Dia. x 2	Top	1400	0.5
		2 Dia. x 2	Top	1400	2.5
		5 Dia. x 5	--	1400	1.0
3	3359	2 Dia. x 2	Bottom	1300	1.0
		2 Dia. x 2	Bottom	1350	1.0
		2 Dia. x 2	Bottom	1400	1.0
		2 Dia. x 2	Top	1400	1.0
		2 Dia. x 2	Top	1400	1.0
		2 Dia. x 2	Bottom	1450	1.0
		2 Dia. x 2	Top	1400	2.5
		2 Dia. x 2	Top	1400	2.5
		5 Dia. x 5	--	1400	1.0
4	3363	2 Dia. x 2	Bottom	1300	1.0
		2 Dia. x 2	Bottom	1350	1.0
		2 Dia. x 2	Bottom	1400	1.0
		2 Dia. x 2	Top	1400	1.0
		2 Dia. x 2	Top	1400	1.0
		2 Dia. x 2	Bottom	1450	1.0
		2 Dia. x 2	Top	1400	2.5
		2 Dia. x 2	Top	1400	2.5
		5 Dia. x 5	--	1400	1.0
4	3364	2 Dia. x 2	Bottom	1300	1.0
		2 Dia. x 2	Bottom	1350	1.0
		2 Dia. x 2	Bottom	1400	1.0
		2 Dia. x 2	Top	1400	1.0
		2 Dia. x 2	Top	1400	1.0
		2 Dia. x 2	Bottom	1450	1.0
		2 Dia. x 2	Top	1400	0.5
		2 Dia. x 2	Top	1400	2.5
		5 Dia. x 5	--	1400	1.0

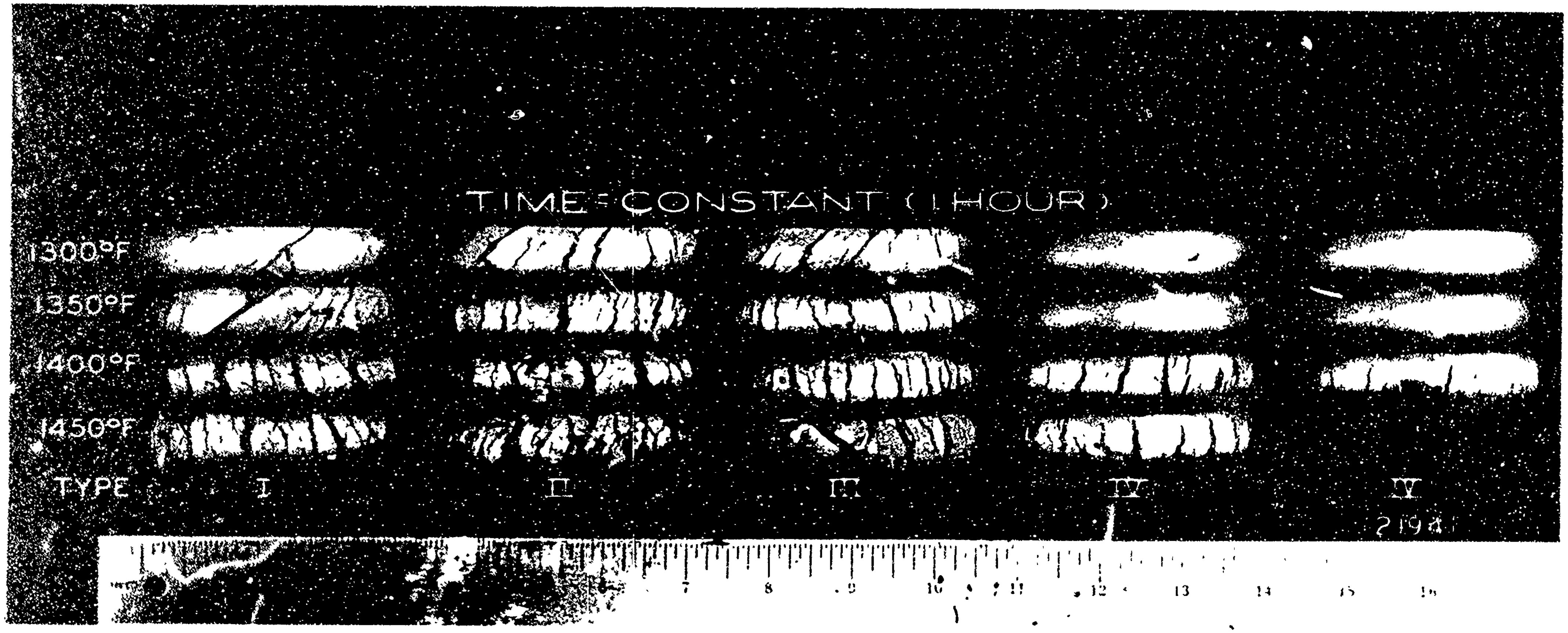


FIGURE 17

UPSET-FORGED FORGEABILITY DISCS SHOWING EFFECT OF FORGING TEMPERATURE

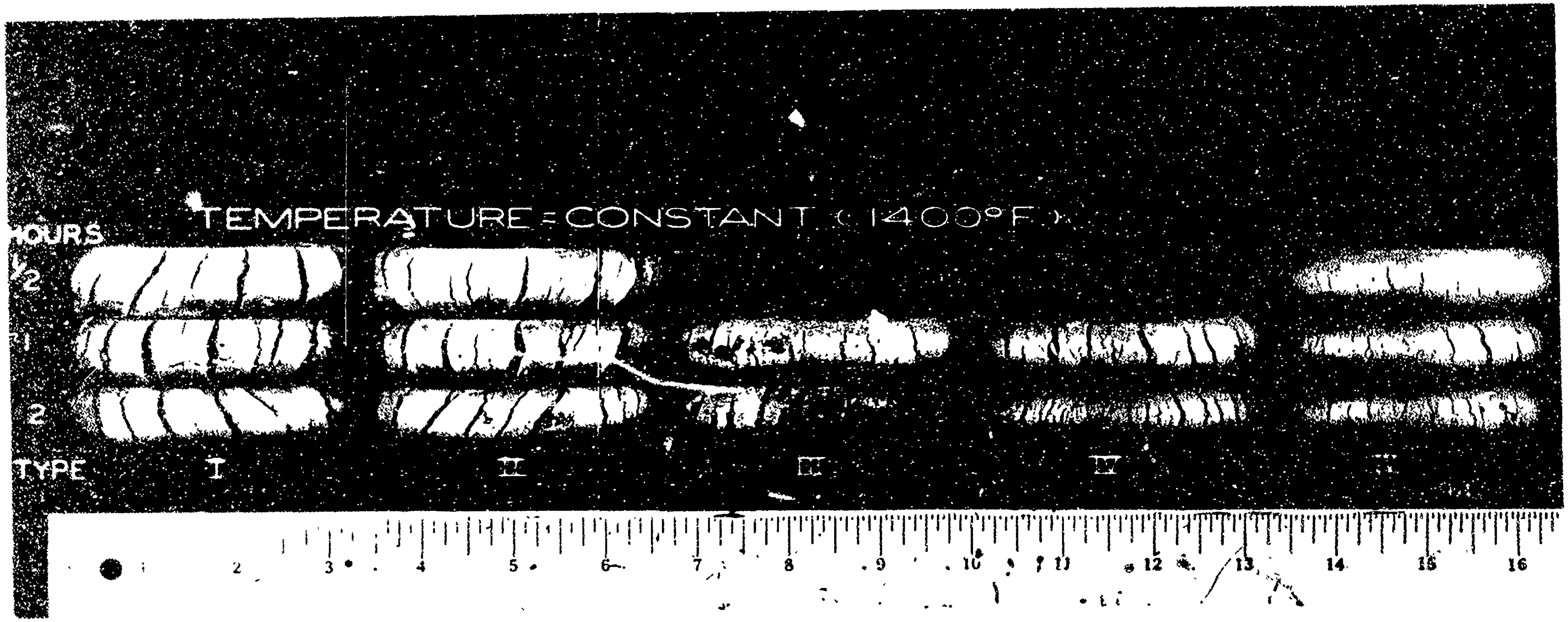


FIGURE 18

UPSET-FORGED FORGEABILITY DISCS SHOWING EFFECT OF TIME AT FORGING TEMPERATURE

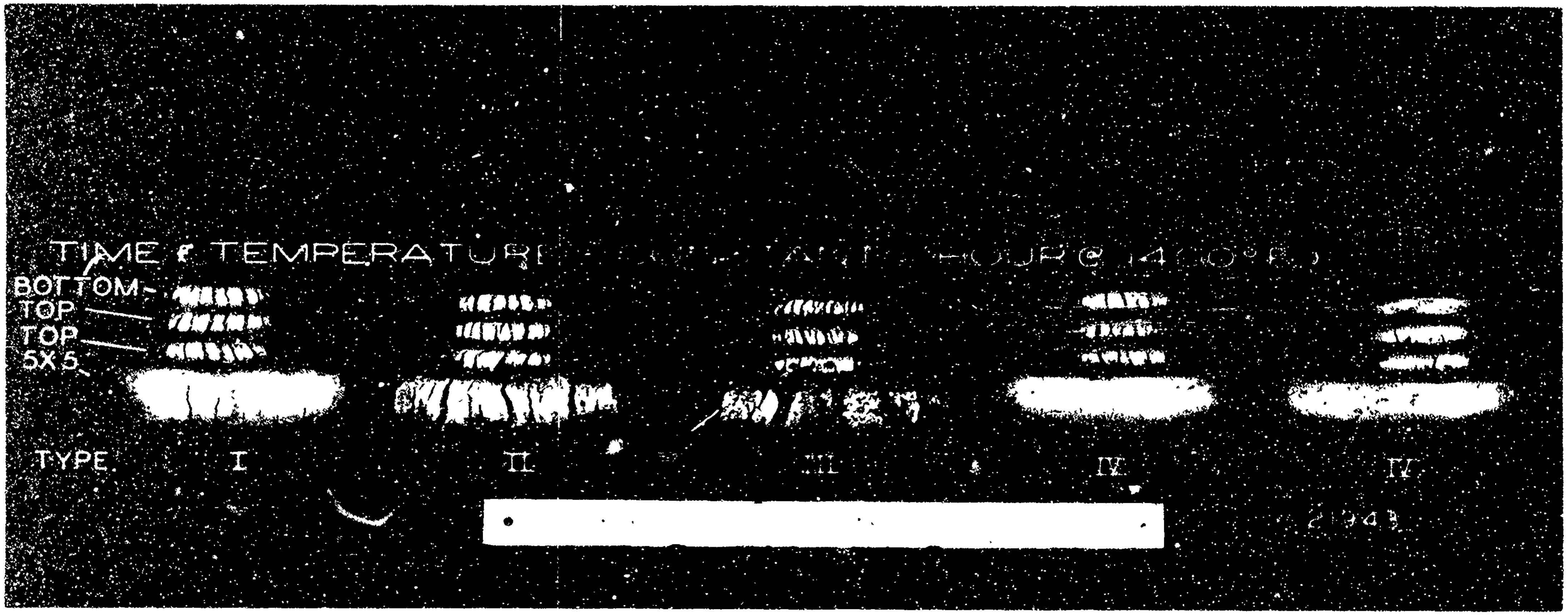


FIGURE 19

UPSET-FORGED FORGEABILITY DISCS SHOWING EFFECT OF BILLET SIZE AND POSITION

TABLE VI

FORGEABILITY INDEX TEST RESULTS OF BERYLLIUM BILLETS FOR MATERIALS EVALUATION

Material Type	Heat No.	Billet Position	Heating Temperature (°F)	Time at Temperature (Hours)	Forgeability Index (per cent)
1	3362	Bottom	1300	1.0	79.5
		Bottom	1350	1.0	69.2
		Bottom	1400	1.0	59.2
		Top	1400	1.0	66.1
		Top	1400	1.0	52.6
		Bottom	1450	1.0	37.5
		Top	1400	0.5	67.3
		Top	1400	2.5	66.0
		5"Dia.x5	1400	1.0	89.5
2	3258	Bottom	1300	1.0	65.8
		Bottom	1350	1.0	67.2
		Bottom	1400	1.0	57.5
		Top	1400	1.0	62.7
		Bottom	1450	1.0	31.5
		Top	1400	0.5	67.6
		Top	1400	2.5	52.6
		5"Dia.x5	1400	1.0	54.0
3	3259	Bottom	1300	1.0	68.0
		Bottom	1350	1.0	79.4
		Bottom	1400	1.0	37.9
		Top	1400	1.0	57.2
		Top	1400	1.0	77.0
		Bottom	1450	1.0	50.3
		Top	1400	2.5	40.4
		Top	1400	2.5	47.0
		5"Dia.x5	1400	1.0	50.0
4	3363	Bottom	1300	1.0	100.0
		Bottom	1350	1.0	100.0
		Bottom	1400	1.0	71.7
		Top	1400	1.0	74.6
		Top	1400	1.0	55.2
		Bottom	1450	1.0	72.0
		Top	1400	2.5	74.8
		Top	1400	2.5	60.3
		5"Dia.x5	1400	1.0	100.0
4	3364	Bottom	1300	1.0	100.0
		Bottom	1350	1.0	100.0
		Bottom	1400	1.0	84.3
		Top	1400	1.0	85.4
		Top	1400	1.0	78.5
		Bottom	1450	1.0	*
		Top	1400	0.5	89.5
		Top	1400	2.5	80.2
		5"Dia.x5	1400	1.0	100.0

* Test Invalid.

TABLE VII

ROOM TEMPERATURE MECHANICAL PROPERTY DATA FROM FORGED UPSETS OF HEAT NO. 3362, TYPE 1 MATERIAL

Billet Size (inches)	Forging Temperature (°F)	Time at Temperature (Hours)	Test Direction	Fty at 0.2% Offset (Ksi)	Ftu (Ksi)	Elongation (per cent)	Reduction of Area (per cent)	Impact Strength (ft-lbs.) Notched Specimen	Impact Strength (ft-lbs.) Unnotched Specimen
2 Dia.x2	1300	1.0	Diametral	73.6 76.1	98.0 97.2	13 16	16 17		6.1
2 Dia.x2	1350	1.0	Diametral	76.9 70.1	97.6 95.8	20 16	18 17		19.0
2 Dia.x2	1400	1.0	Diametral	68.0 69.8	95.7 98.8	18 15	17 25		19.0
2 Dia.x2	1400	1.0	Diametral	62.6 65.4	89.6 93.7	12 16	12 18		18.4
2 Dia.x2	1400	1.0	Diametral	61.2 61.7	94.7 91.1	11 19	12 22		*
2 Dia.x2	1450	1.0	Diametral	53.8 53.5	88.9 90.8	14 16	14 18		16.6
2 Dia.x2	1400	0.5	Diametral	63.5 63.1	90.9 91.2	13 17	19 18		20.4
2 Dia.x2	1400	2.5	Diametral	65.0 65.1	89.8 91.2	12 16	14 17		21.5
5 Dia.x5	1400	1.0	Circumferential	62.3 63.1	86.5 86.6	12 7	13 6	0.25	13.8
5 Dia.x5	1400	1.0	Radial	63.0 63.0	90.8 87.4	12 6	14 6	0.32	**
5 Dia.x5	1400	1.0	Axial	*** ***	50.6 56.3			0.19	0.48

* Insufficient material.
** Cracked during machining.
*** Failed in gage length before attaining 0.2 per cent offset strain.

TABLE VIII

ROOM TEMPERATURE MECHANICAL PROPERTY DATA FROM FORGED UPSETS OF HEAT NO. 3258, TYPE 2 MATERIAL

Billet Size (Inches)	Forging Temperature (°F)	Time at Temperature (Hours)	Test Direction	Fty at 0.2% Offset (Ksi)	Ftu (Ksi)	Elongation (per cent)	Reduction of Area (per cent)	Impact Strength (ft-lbs.)	
								Notched Specimen	Unnotched Specimen
2 Dia.x2	1300	1.0	Diametral	60.8 61.7	93.8 90.2	11 22	10 23		9.9
2 Dia.x2	1350	1.0	Diametral	58.1 58.1	90.0 90.9	18 22	23 24		2.6
2 Dia.x2	1400	1.0	Diametral	58.2 57.-	90.6 93.1	24 17	24 19		26.2
2 Dia.x2	1400	1.0	Diametral	60.9 59.0	92.8 91.8	26 16	28 20		16.4
2 Dia.x2	1400	1.0	Diametral	62.2 59.8	93.1 92.8	21 23	23 26		4.3
2 Dia.x2	1450	1.0	Diametral	57.7 57.3	87.1 89.6	9 16	10 18		*
2 Dia.x2	1400	0.5	Diametral	56.2 55.6	88.6 89.1	14 16	15 18		19.2
2 Dia.x2	1400	2.5	Diametral	60.0 62.7	94.2 93.0	17 19	17 21		10.4
5 Dia.x5	1400	1.0	Circumferential	60.2 55.0	84.4 82.4	6 10	8 12	0.30	19.2
5 Dia.x5	1400	1.0	Radial	57.1 56.7	80.9 85.7	5 13	6 14	0.19	16.2
5 Dia.x5	1400	1.0	Axial	** **	57.8 54.5			0.19	0.30

* Insufficient material.
** Failed in gage length before attaining 0.2 per cent offset strain.

TABLE IX

ROOM TEMPERATURE MECHANICAL PROPERTY DATA FROM FORGED UPSETS OF
HEAT NO. 3259, TYPE 3 MATERIAL

Billet Size (inches)	Forging Temperature (°F)	Time at Temperature (Hours)	Test Direction	Fty at 0.2% Offset (Ksi)	Ftu (Ksi)	Elongation (per cent)	Reduction of Area (per cent)	Impact Strength (ft-lbs.) Notched Specimen	Unnotched Specimen
2 Dia.x2	1300	1.0	Diametral	56.9 60.8	87.4 91.3	15 14	15 16		24.2
2 Dia.x2	1350	1.0	Diametral	71.1 69.0	94.3 94.4	15 13	18 12		6.1
2 Dia.x2	1400	1.0	Diametral	52.9 55.6	90.9 88.4	14 16	14 21		*
2 Dia.x2	1400	1.0	Diametral	52.4 54.5	88.4 89.5	13 15	15 20		24.5
2 Dia.x2	1400	1.0	Diametral	66.2 67.8	91.7 93.3	9 10	10 11		18.6
2 Dia.x2	1450	1.0	Diametral	60.8 63.2	92.3 90.4	12 11	13 12		17.4
2 Dia.x2	1400	2.5	Diametral	52.0 51.0	86.9 84.3	11 12	11 13		**
2 Dia.x2	1400	2.5	Diametral	55.2 54.1	89.2 89.1	17 20	20 21		8.8
5 Dia.x5	1400	1.0	Circumferential	51.0 50.9	83.8 78.0	10 7	9 7	0.21	5.6
5 Dia.x5	1400	1.0	Radial	51.1 52.0	79.5 86.6	10 15	12 15	0.19	11.4
5 Dia.x5	1400	1.0	Axial	*** ***	52.8 55.3			0.16	**

* Insufficient material.
** Cracked during machining.
*** Failed in gage length before attaining 0.2 per cent offset strain.

TABLE X

ROOM TEMPERATURE MECHANICAL PROPERTY DATA FROM FORGED UPSETS OF HEAT NO. 3363, TYPE 4 MATERIAL

Billet Size (inches)	Forging Temperature (°F)	Time at Temperature (Hours)	Test Direction	Fty at 0.2% Offset (Ksi)	Ftu (Ksi)	Elongation (per cent)	Reduction of Area (per cent)	Impact Strength (ft-lbs.) Notched Specimen	Unnotched Specimen
2 Dia.x2	1300	1.0	Diametral	72.0 68.0	97.8 93.6	13 17	19 21		**
2 Dia.x2	1350	1.0	Diametral	70.8 69.9	94.3 96.9	10 11	17 17		**
2 Dia.x2	1400	1.0	Diametral	72.5 72.6	97.6 97.6	11 15	13 16		19.0
2 Dia.x2	1400	1.0	Diametral	68.1 69.0	94.8 94.6	18 14	20 15		28.9
2 Dia.x2	1400	1.0	Diametral	51.3 56.1	90.6 88.1	11 17	13 22		9.1
2 Dia.x2	1450	1.0	Diametral	71.4 66.3	96.9 96.8	21 15	26 16		*
2 Dia.x2	1400	2.5	Diametral	71.5 72.9	96.3 96.4	20 22	25 25		4.4
2 Dia.x2	1400	2.5	Diametral	55.7 55.0	89.3 92.1	15 18	20 18		15.4
5 Dia.x5	1400	1.0	Circumferential	63.8 64.8	91.2 93.6	16 14	24 19	0.34	11.6
5 Dia.x5	1400	1.0	Radial	64.0 66.4	87.3 90.5	5 5	7 6	0.41	19.0
5 Dia.x5	1400	1.0	Axial	*** ***	60.5 50.5			0.19	0.25

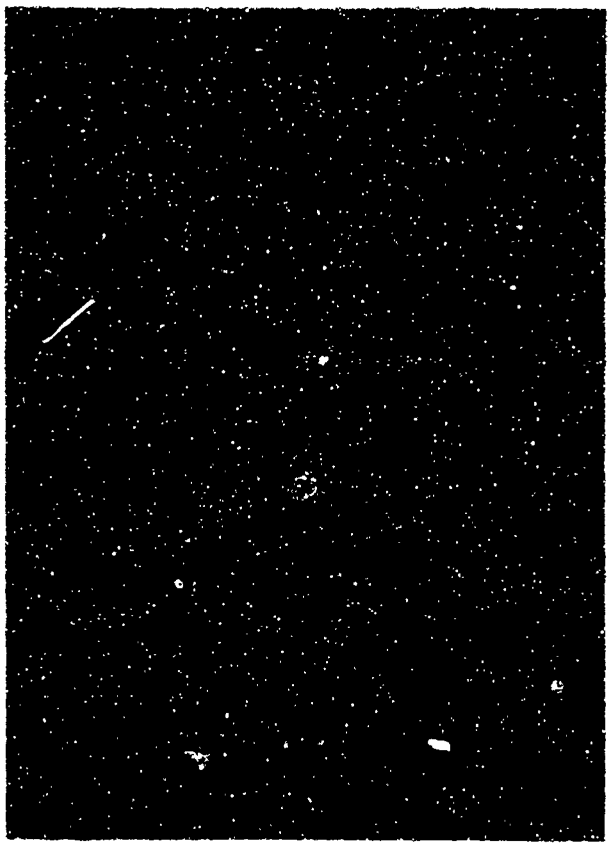
* Insufficient material.
** Cracked during machining.
*** Failed in gage length before attaining 0.2 per cent offset strain.

TABLE XI

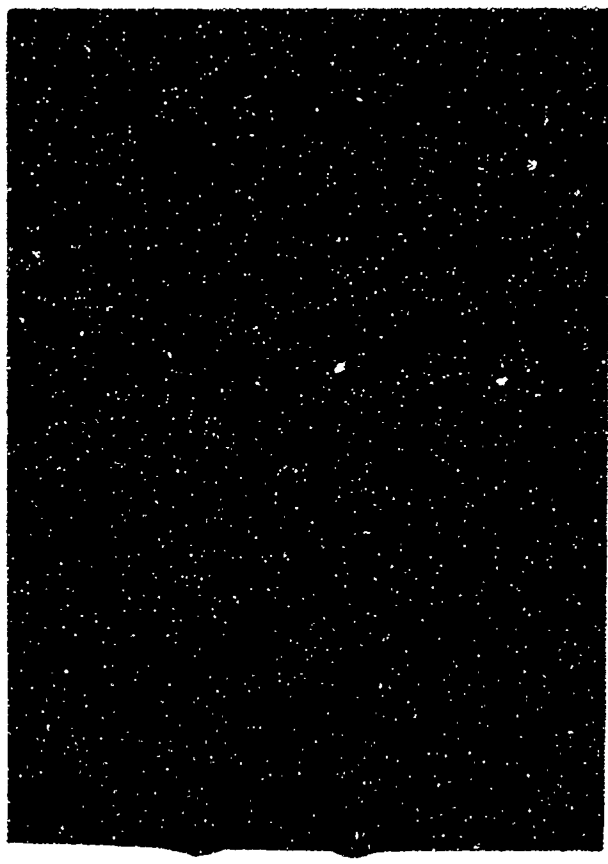
ROOM TEMPERATURE MECHANICAL PROPERTY DATA FROM FORGED UPSETS OF HEAT NO. 3364, TYPE 4 MATERIAL

Billet Size (inches)	Forging Temperature (°F)	Time at Temperature (Hours)	Test Direction	Fty at 0.2% Offset (Ksi)	Ftu (Ksi)	Elongation (per cent)	Reduction of Area (per cent)	Impact Strength (ft-lbs.) Notched Specimen	Unnotched Specimen
2 Dia.x2	1300	1.0	Diametral	66.4 72.2	91.1 97.9	13 17	17 20		15.1
2 Dia.x2	1350	1.0	Diametral	65.0 67.1	90.7 90.7	15 11	19 15		21.3
2 Dia.x2	1400	1.0	Diametral	70.5 70.2	95.5 94.2	21 20	22 20		15.7
2 Dia.x2	1400	1.0	Diametral	69.0 86.9	94.2 95.3	8 11	11 12		23.4
2 Dia.x2	1400	1.0	Diametral	72.0 72.0	98.5 96.7	15 16	18 20		9.2
2 Dia.x2	1450	1.0	Diametral	*					
2 Dia.x2	1400	0.5	Diametral	71.8 68.5	97.6 96.0	15 14	17 14		**
2 Dia.x2	1400	2.5	Diametral	71.6 71.3	95.9 97.2	9 13	10 15		4.3
5 Dia.x5	1400	1.0	Circumferential	69.8 68.2	81.1 95.0	2 14	3 17	0.34	10.7
5 Dia.x5	1400	1.0	Radial	67.0 67.3	91.0 85.7	8 2	11 4	0.25	13.5
5 Dia.x5	1400	1.0	Axial	*** ***	57.4 60.4			0.12	0.23

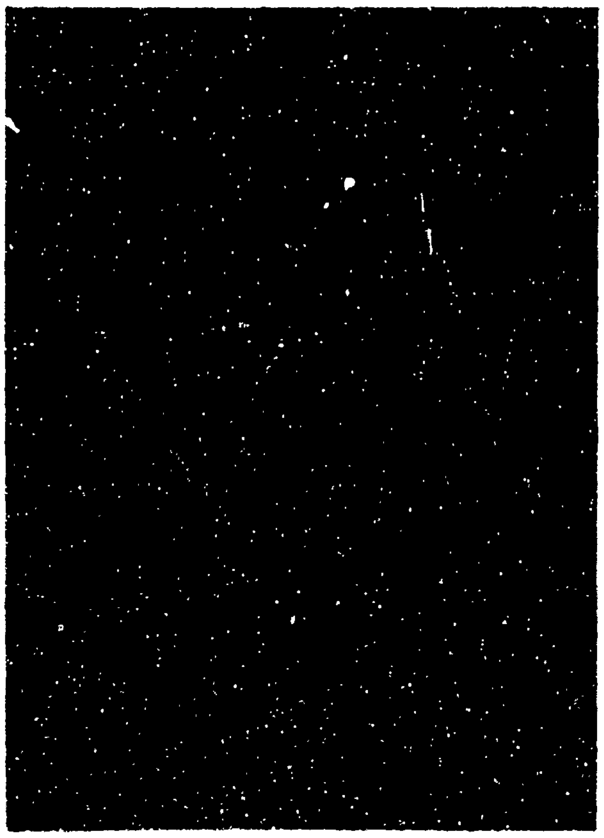
* Forgeability test invalid.
** Cracked during machining.
*** Failed in gage length before attaining 0.2 per cent offset strain.



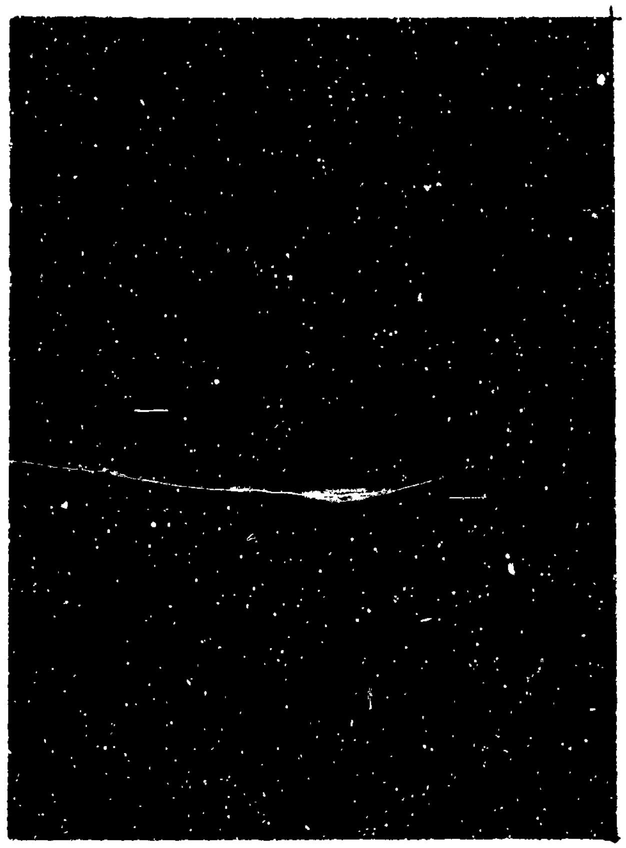
Top Billet Position
500X Magnification



Top Billet Position
500X Magnification



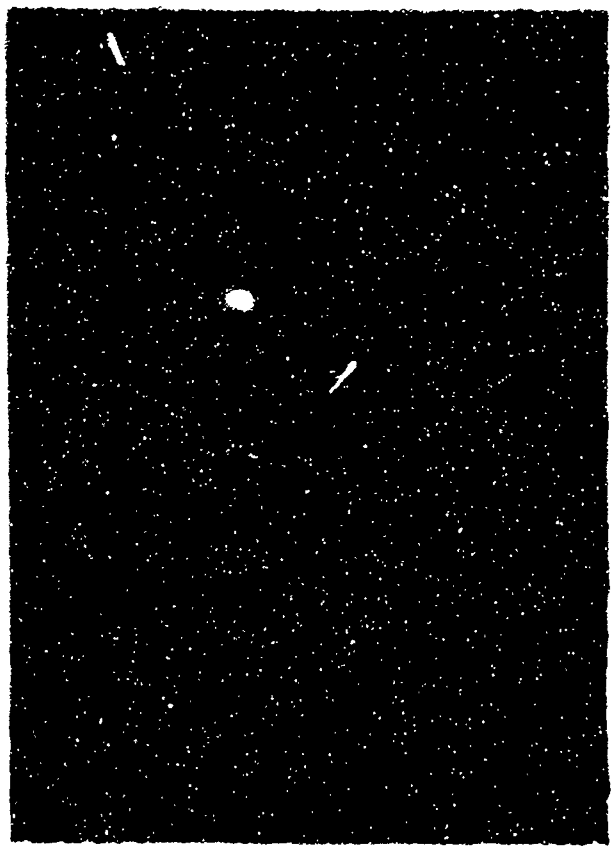
Bottom Billet Position
500X Magnification



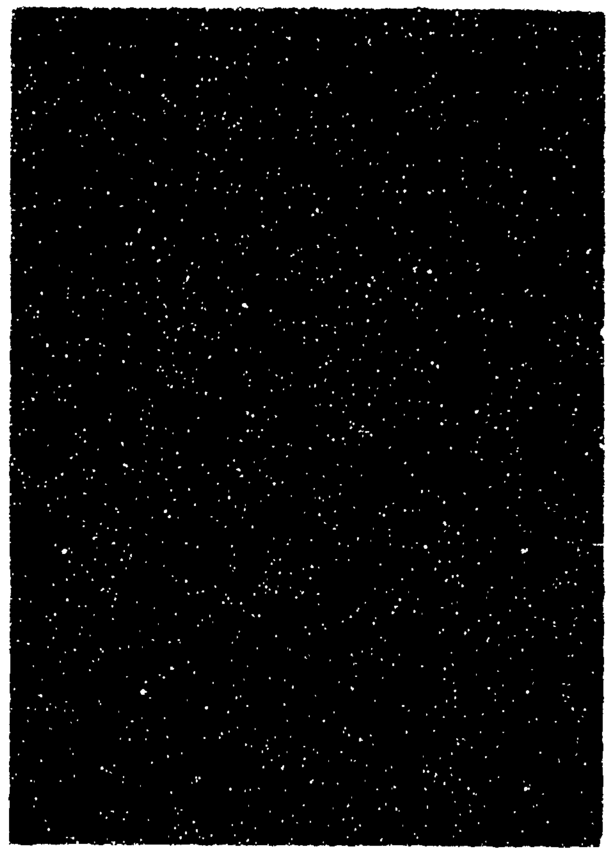
Bottom Billet Position
1500X Magnification
Electron Microscope

FIGURE 20

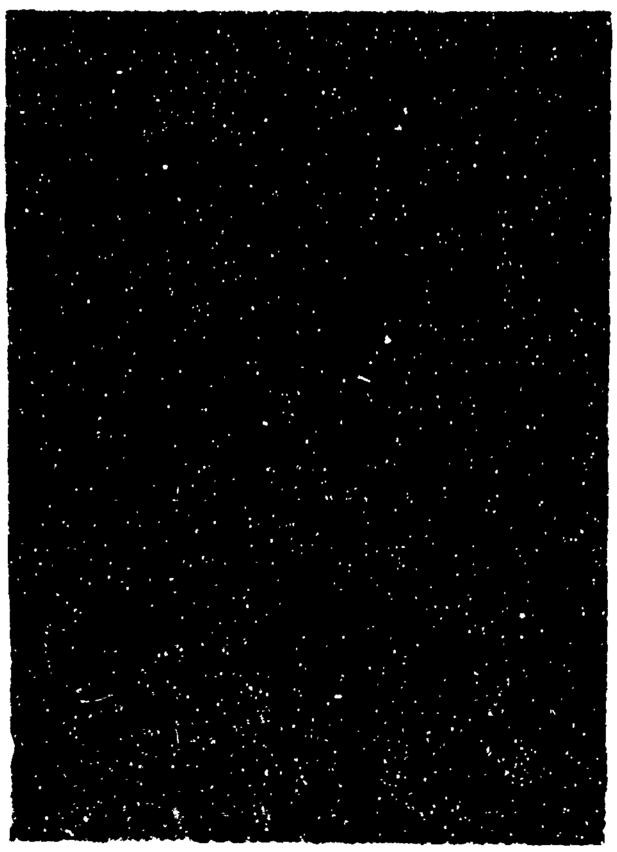
MICROSTRUCTURE OF THREE FORGEABILITY DISCS. Heated for one hour at 1400°F and upset-forged to a height reduction of 60 per cent. Heat No. 3362, Type 1 Material, Outer Diameter Location, Radial-Axial Plane, Etched.



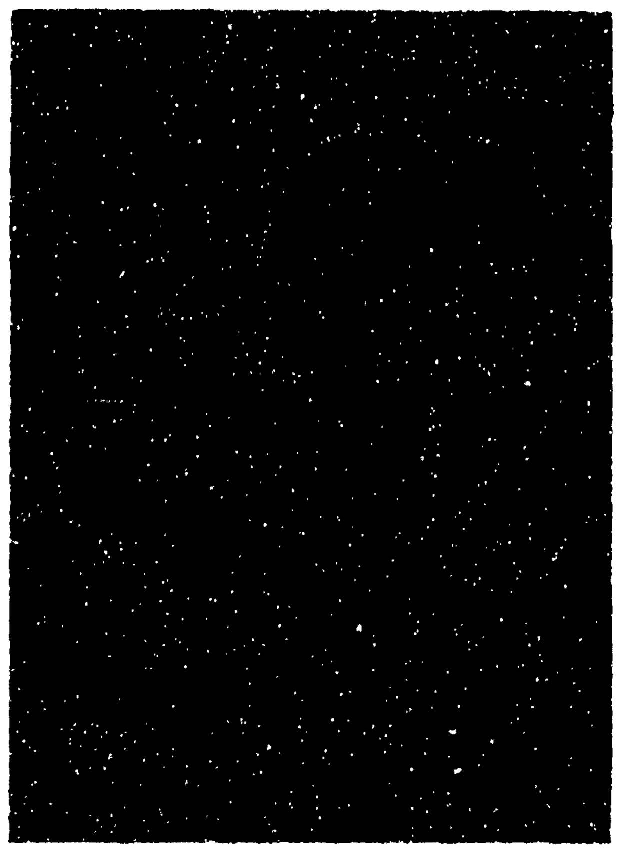
Top Billet Position
500X Magnification



Top Billet Position
500X Magnification



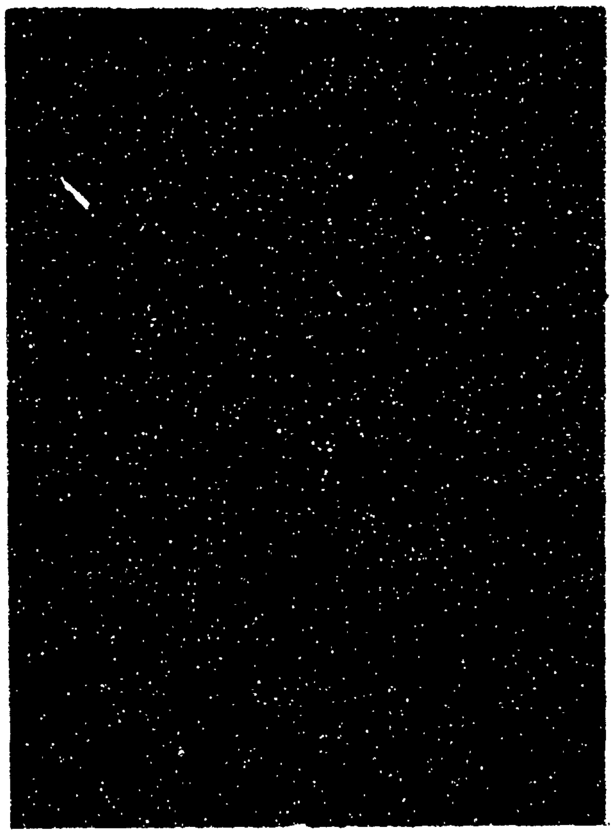
Bottom Billet Position
500X Magnification



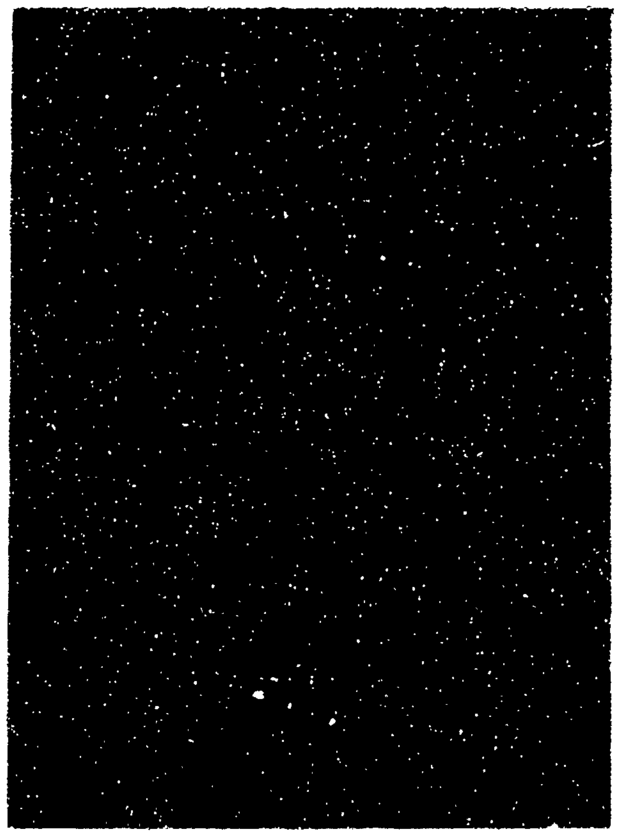
Bottom Billet Position
1500X Magnification
Electron Microscope

FIGURE 21

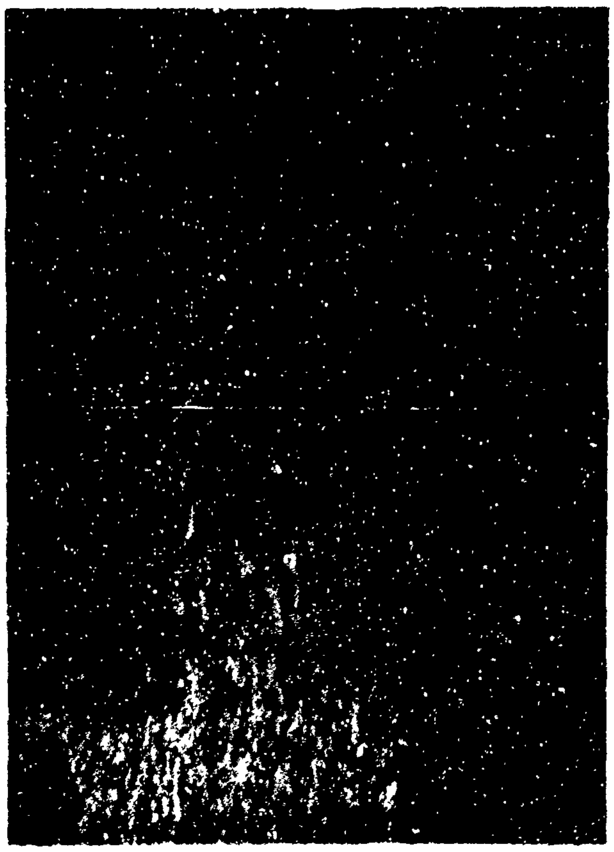
MICROSTRUCTURE OF THREE FORGEABILITY DISCS. Heated for one hour at 1400°F and upset-forged to a height reduction of 60 per cent. Heat No. 3258, Type 2 Material, Outer Diameter Location, Radial-Axial Plane, Etched.



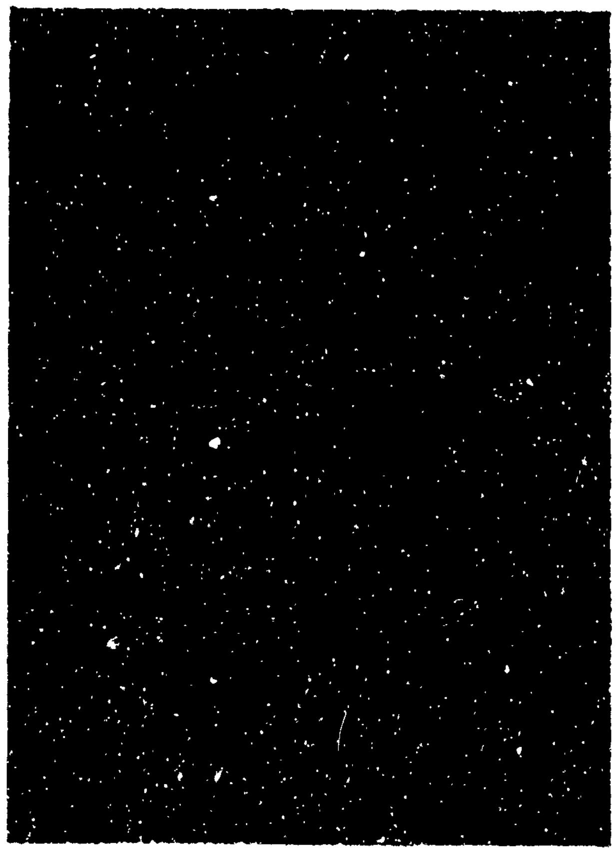
Top Billet Position
500X Magnification



Top Billet Position
500X Magnification



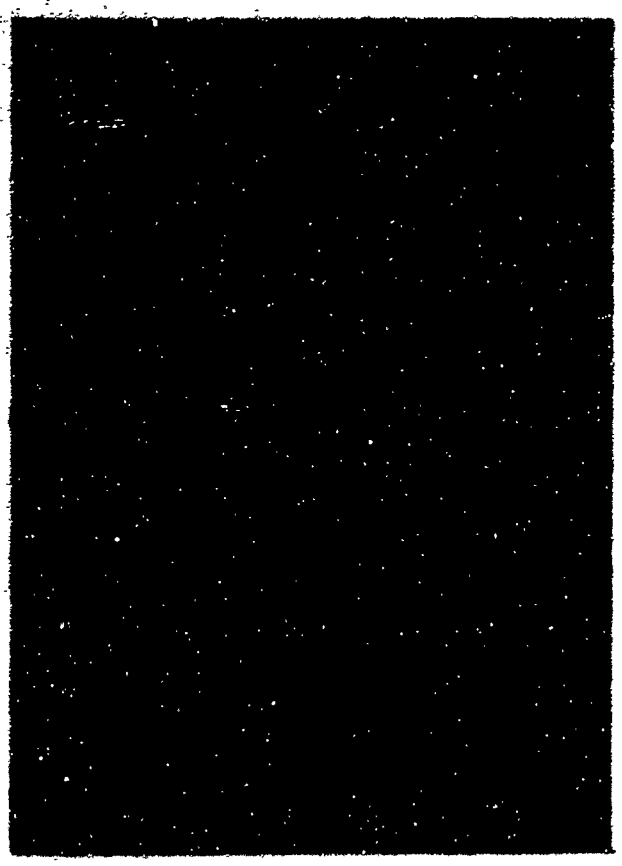
Bottom Billet Position
500X Magnification



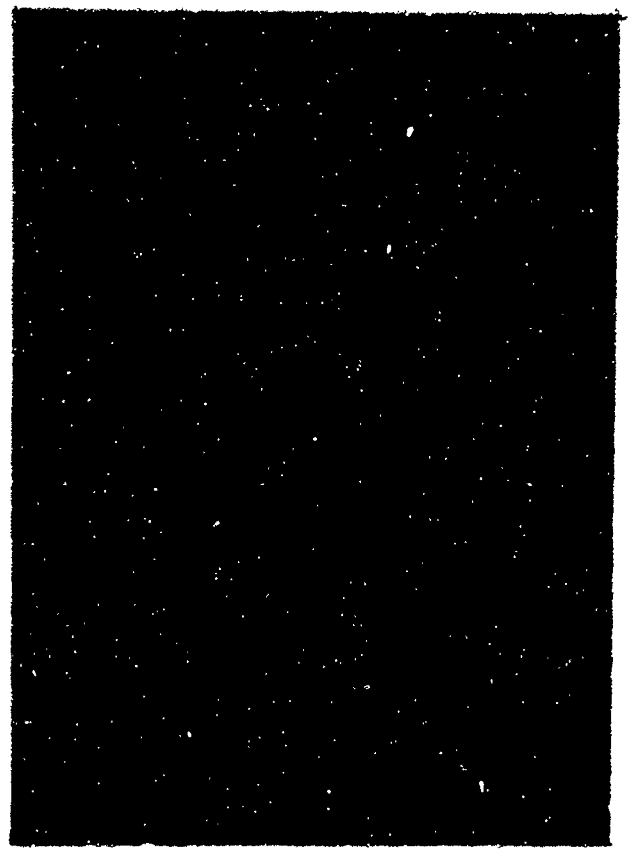
Bottom Billet Position
1500X Magnification
Electron Microscope

FIGURE 22

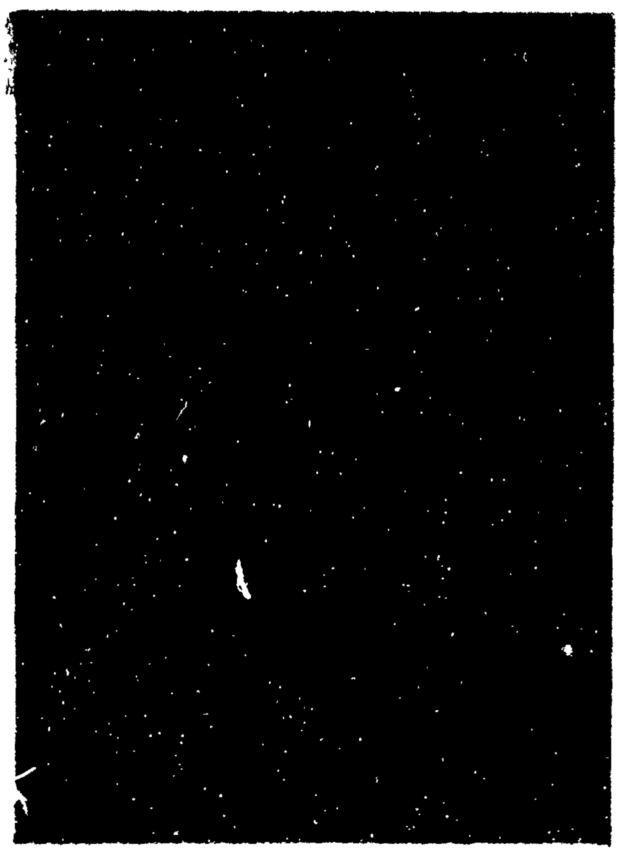
MICROSTRUCTURE OF THREE FORGEABILITY DISCS. Heated for one hour at 1400°F and upset-forged to a height reduction of 60 per cent. Heat No. 3259, Type 3 Material, Outer Diameter Location, Radial-Axial Plane, Etched.



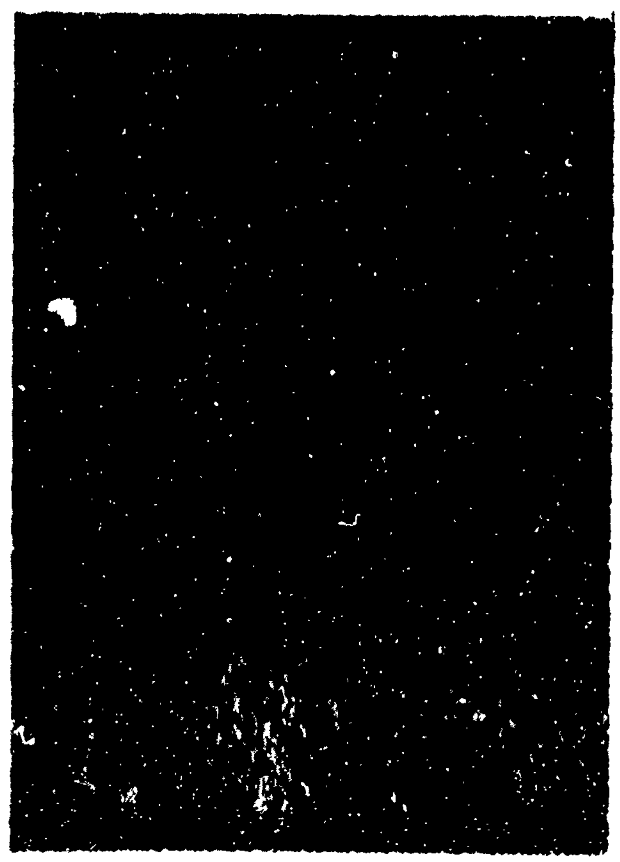
Top Billet Position
500X Magnification



Top Billet Position
500X Magnification



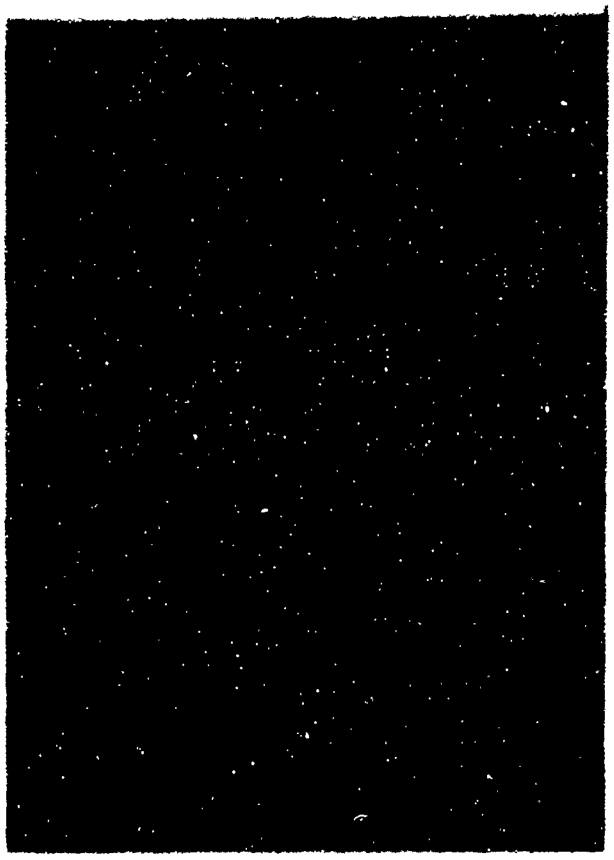
Bottom Billet Position
500X Magnification



Bottom Billet Position
1500X Magnification
Electron Microscope

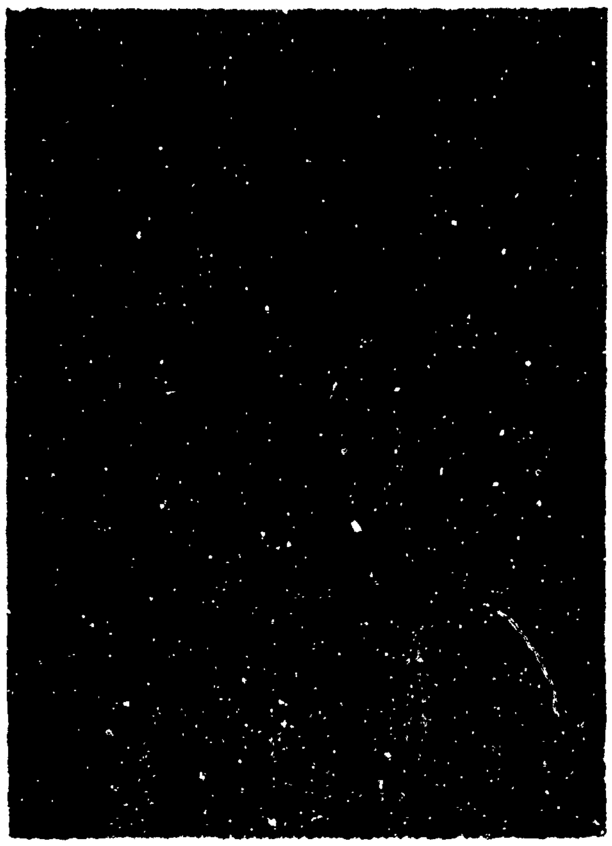
FIGURE 23

MICROSTRUCTURE OF THREE FORGEABILITY DISCS. Heated for one hour at 1400°F and upset-forged to a height reduction of 60 per cent. Heat No. 3363, Type 4 Material, Outer Diameter Location, Radial-Axial Plane, Etched.



Top Billet Position
500X Magnification

Top Billet Position
500X Magnification



Bottom Billet Position
500X Magnification

Bottom Billet Position
1500X Magnification
Electron Microscope

FIGURE 24

MICROSTRUCTURE OF THREE FORGEABILITY DISCS. Heated for one hour at 1400°F and upset-forged to a height reduction of 60 per cent. Heat No. 3364, Type 4 Material, Outer Diameter Location, Radial-Axial Plane, Etched.

C. Discussion

The metallographic evaluation of the vacuum-hot-pressed billet material showed that structural differences do exist, such as the size and appearance of grain-boundary precipitates or inclusions, the degree of continuity of grain-boundary precipitates, appearance of stringers, etc. Types 1, 2, and 3 beryllium have a more continuous network of grain-boundary precipitates and the precipitate particles are larger and more distinct than those of the Type 4 heats. The precipitate in the Type 4 material exists more as a cluster rather than as a semi-continuous network. The structure of Type 4 also has a "feathery" appearance and lacks the "blended" characteristic of Types 1, 2, and 3.

A review of the tensile test data shows a significant, though unexplained, correlation with forgeability. A plot of the forgeability index versus yield strength for Type 1 material is presented in Figure 25, which indicates a decrease in forgeability as yield strength decreases. This trend is less apparent for the other heats of beryllium where less spread in the yield strength existed.

The forgeability results showed some lack of reproducibility for the duplicate samples heated at 1400°F for one hour and forged. These inconsistencies are sometimes explained by non-uniformity in surface preparation, lubrication, die temperature, heating temperature, etc. The inconsistencies in question, however, showed the yield strength drop discussed above. Surface preparation, lubrication, and die temperature are essentially surface considerations and could not be expected to have a significant effect upon yield strength by themselves. Heating temperature was carefully controlled using a separate thermocouple in a sample block, placed in the midst of the forging specimens. Temperature variation did not exceed ±10°F.

Billet position is another possible explanation for non-uniform results; however, the instances of greatest non-uniformity occurred between adjacent samples. Analysis of potential variables must include strain rate as a possible source of inconsistency. Samples were forged in a unit capable of upset-forging both the two-inch-diameter by two-inch-high and the five-inch-diameter by five-inch-high specimens. The plan area of the larger-size samples after forging required use of a relatively large press and forging of these larger samples proceeded in a normal manner with a visible decrease in strain rate toward the end of the stroke. However, the forging rate for the two-inch-diameter by two-inch-high specimens was higher and subject to operator variation which may have been significant. The smaller beryllium samples were so overpowered that it is questionable whether the forging rate diminished or was higher the moment before completion of the stroke.

It should be recognized, however, that in spite of instances of inconsistency in test results between samples which should have

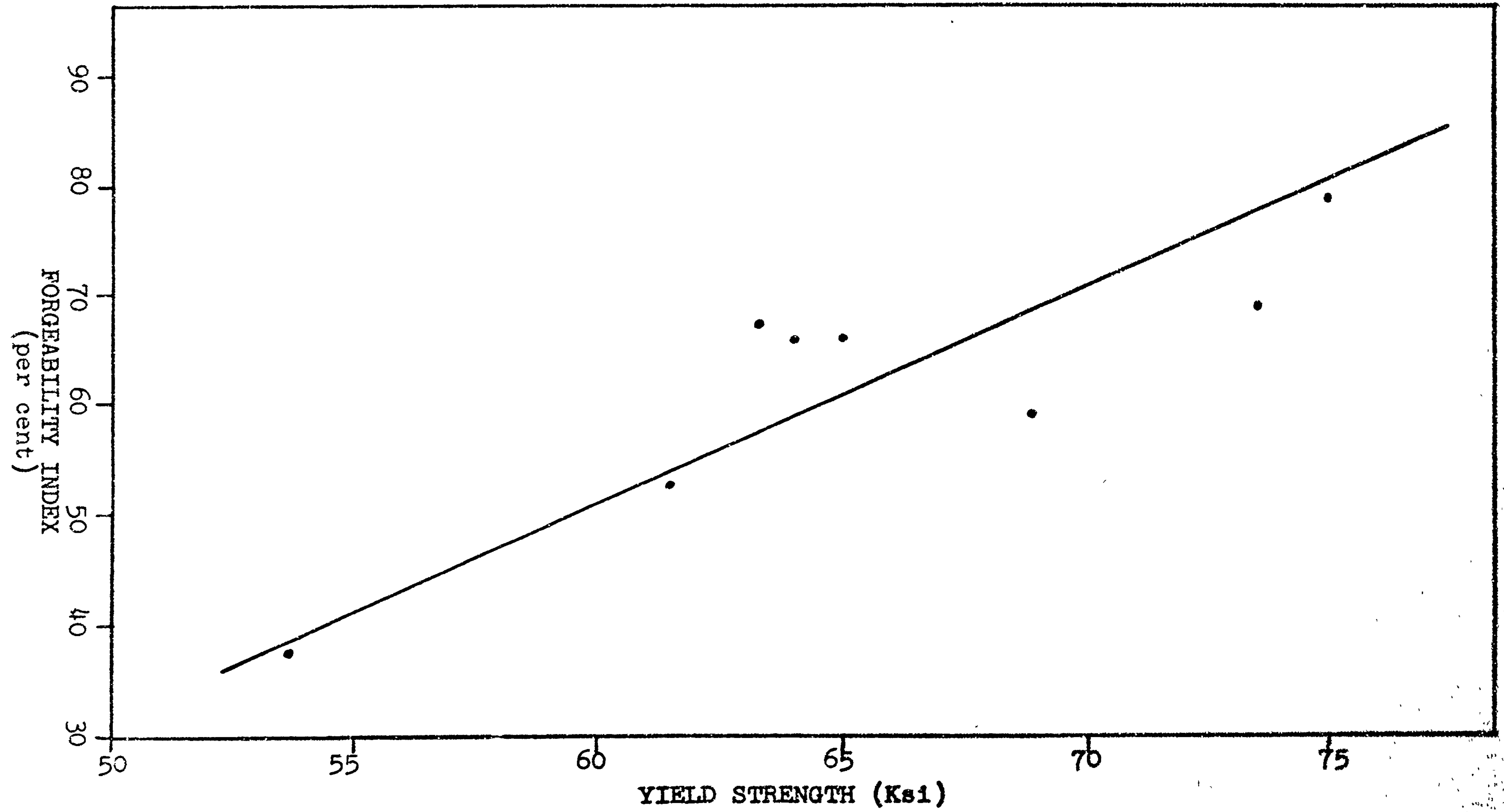


FIGURE 25: FORGEABILITY INDEX VERSUS YIELD STRENGTH FOR THE UPSET-FORGED DISCS FROM HEAT NO. 3362.

produced similar forgeability ratings, the superiority of the Type 4 material was definitely demonstrated for both response to forging and mechanical properties.

A comparison of the average overall forgeability between the five different heats of beryllium investigated is shown in Figure 26. The Type 4 heats show the highest forgeabilities over the other grades investigated. Figure 27 compares the forgeability of the various heats at different forging temperatures. The curves show that forgeability decreases as forging temperature increases, and again demonstrates the superior forgeability of Type 4 beryllium. Subsequent forging was conducted in the 1300 to 1400°F range.

The tensile property results showed good uniformity within heats and between heats investigated, with the exception of the yield strength, as discussed earlier. No definite trends were noted by plotting tensile test results against forging temperature, time at temperature, or billet location.

The Charpy impact test results showed a considerable lack of uniformity. Some difficulty was experienced during machining of the specimens, which may have accounted for some of the scatter in the results. Test blanks had a tendency to crack or chip during milling or grinding. Invalid tests were minimized by eliminating those specimens which showed indications of cracks during dye-penetrant inspection prior to testing. Specimens had been stress-relieved at 1400°F for one-half hour and electropolished to remove 0.002 inch from all surfaces to minimize or remove residual stress and surface micro-cracks.

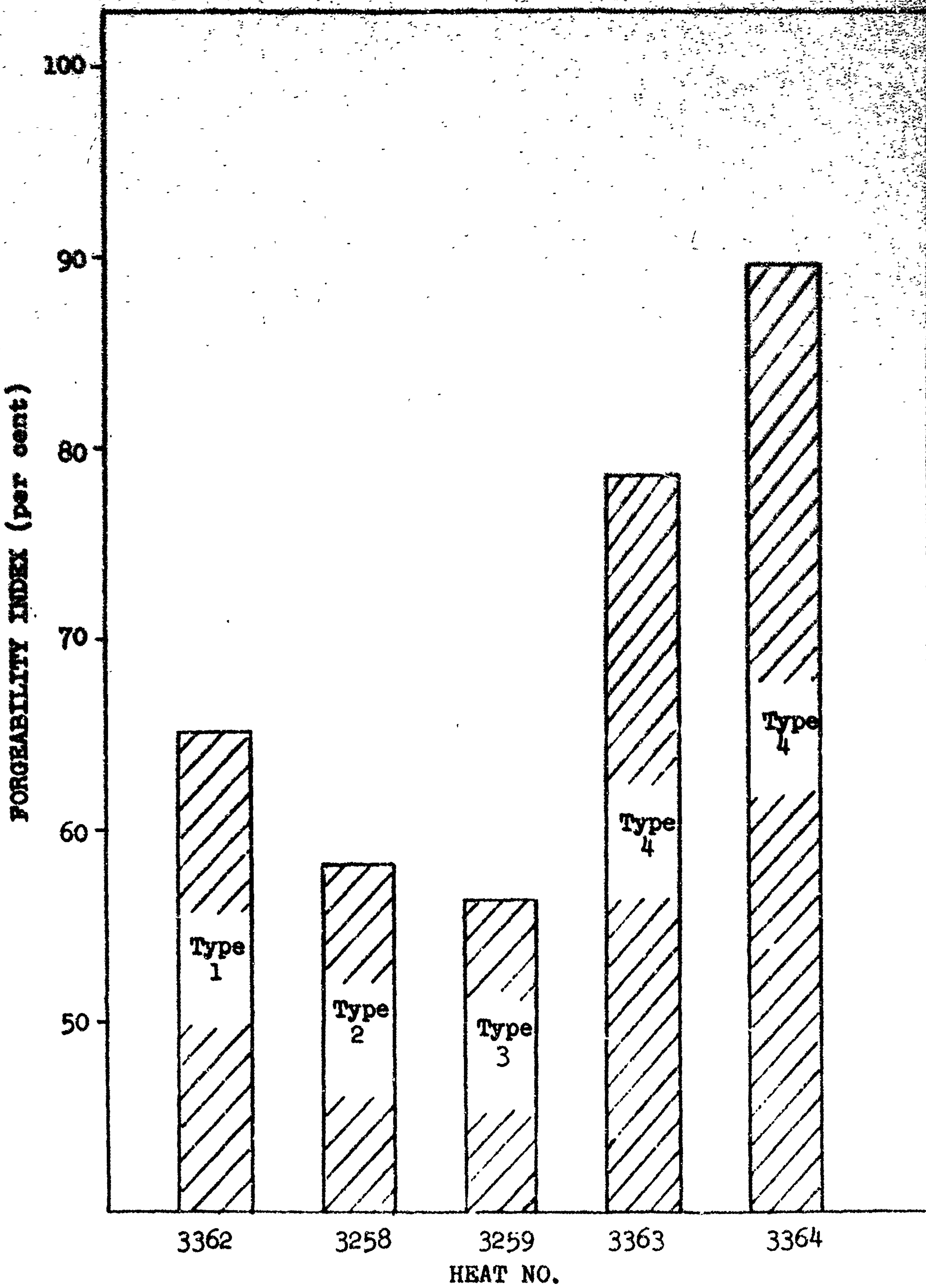


FIGURE 26: COMPARISON OF THE AVERAGE FORGEABILITY OF THE FIVE HEATS OF BERYLLIUM USED FOR THE MATERIALS EVALUATION

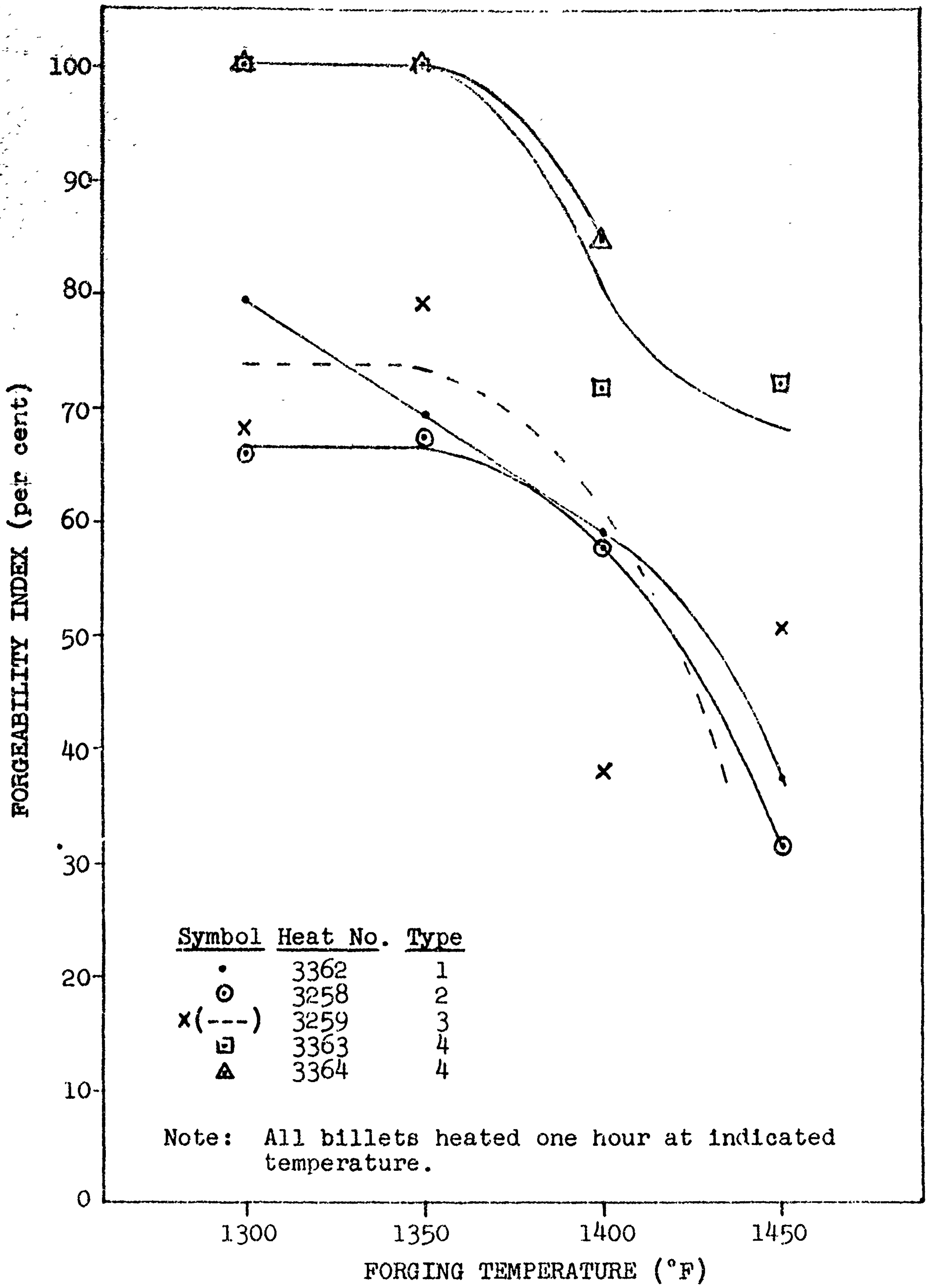


FIGURE 27: THE EFFECT OF FORGING TEMPERATURE UPON THE FORGEABILITY OF THE FIVE HEATS OF BERYLLIUM USED FOR THE MATERIALS EVALUATION

III. ENGINE COMPONENT MANUFACTURE

A. Material

Two Type 4 beryllium billets 8-1/4-inch diameter by 11-1/2 inches high were procured from The Brush Beryllium Company during Phase I for use in Phase II blade development and manufacture. Material was vacuum hot pressed using minus 20 micron virgin powder having the powder particle size distribution shown in Table XII.

TABLE XII

BERYLLIUM POWDER MICROSIEVE ANALYSIS
LOT NO. 3543

PARTICLE SIZE (MICRONS)	PERCENTAGE
Minus 5	27.2
Minus 10	65.5
Minus 15	95.4
Minus 20	98.7
Minus 25	99.5
Minus 30	99.6
Minus 35	100.0

The hot pressing, identified as Lot No. 3543, was analyzed for chemical composition and evaluated for tensile properties. The results are shown in Tables XIII and XIV. The data presented in Tables XII through XIV was furnished by The Brush Beryllium Company.

TABLE XIII

CHEMICAL COMPOSITION OF BERYLLIUM LOT NO. 3543

ELEMENT	AMOUNT	ELEMENT	AMOUNT
Be	97.55%	Ag	4 ppm
BeO	3.21%	Ca	< 85 ppm
C	0.14%	Co	7 ppm
Al	700 ppm*	Cu	80 ppm
Cr	110 ppm	Mo	< 8 ppm
Fe	1072 ppm	Pb	6 ppm
Mg	220 ppm	Si	180 ppm
Mn	108 ppm	Zn	< 55 ppm
Ni	120 ppm	N	231 ppm
Ti	150 ppm		

* ppm indicates parts per million.

TABLE XIV

ROOM TEMPERATURE TENSILE PROPERTIES OF BERYLLIUM LOT NO. 3543 IN THE AS-HOT-PRESSED CONDITION.

TEST DIRECTION	YIELD STRENGTH AT 0.2 PER CENT OFFSET (KSI)	ULTIMATE STRENGTH (KSI)	ELONGATION (PER CENT)
Longitudinal	60.0	80.8	3.0
Transverse	52.9	67.6	1.4

The two billets were inspected for soundness using ultrasonic, dye-penetrant, X-ray, and etch test techniques. Billets were found to be free of defects detectable through use of these techniques.

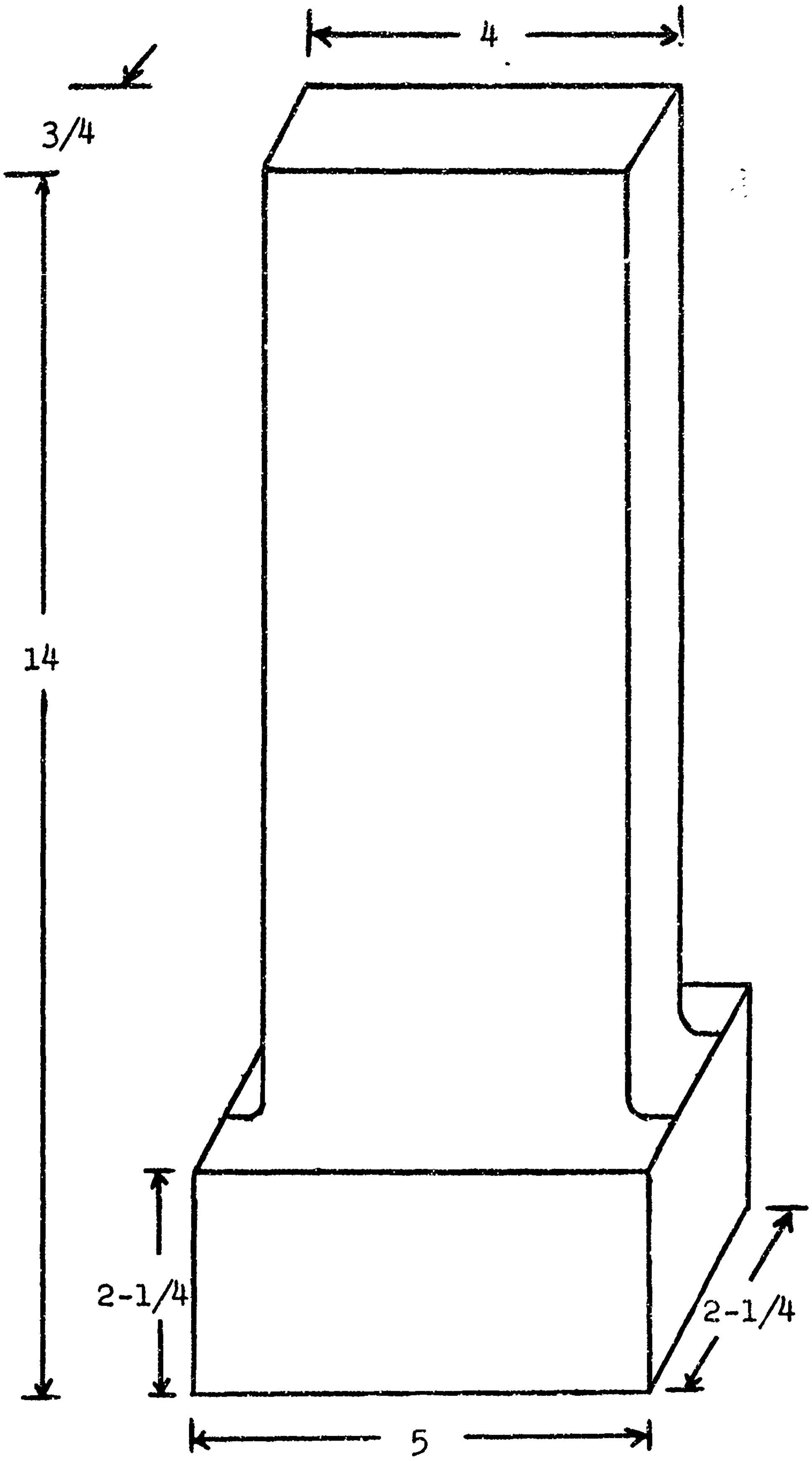
B. Phase II Blade Design and Manufacturing Procedure

The design of the Phase II blade is shown in Figure 28. Blade geometry was kept relatively simple to provide maximum metal utilization for the test program. The blade thickness is governed mainly by the reduction ratio selected for the final operation. A thinner blade could be produced by increasing the extrusion ratio with an accompanying increase of preferred orientation in the airfoil section. At this stage of development, extremes of preferred orientation were being avoided to provide a greater balance of crystallographic orientation in three directions for a determination of the effects of this balance upon mechanical properties.

A schematic of the manufacturing sequence is shown in Figure 29. This approach was based upon experience in multidirectionally forging beryllium.

C. Material Transfer and Blade Manufacture

The two Phase II blade billets purchased for the manufacture of eight test blades were transferred to Contract AF33(615)-2231 for use in Phase IIA of that program. Blades were subsequently manufactured and reported under Contract AF33(615)-2231.



(All dimensions in inches.)

FIGURE 28

BERYLLIUM BLADE CONFIGURATION FOR PHASE II

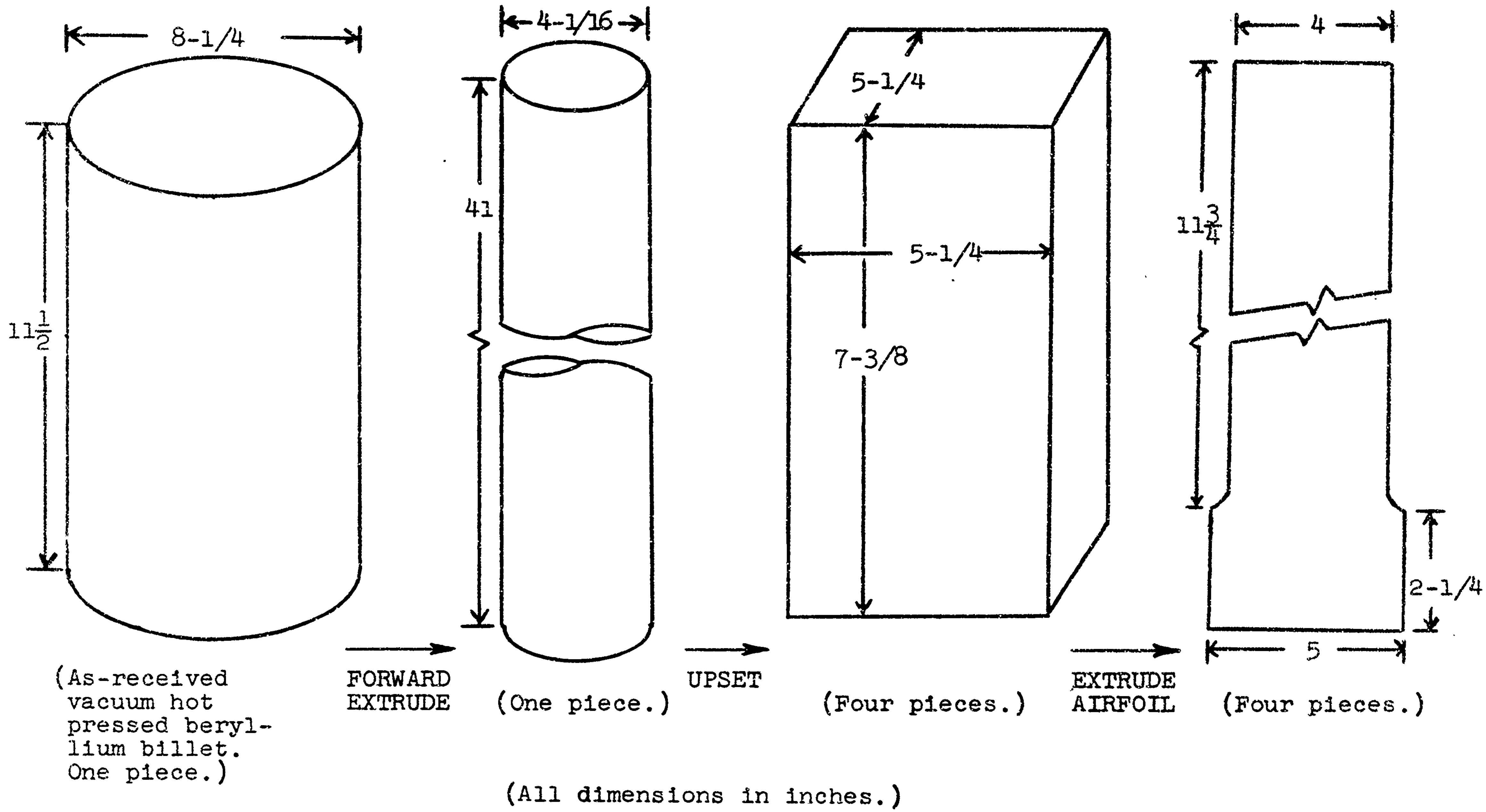


FIGURE 29

SCHEMATIC OF MANUFACTURING SEQUENCE FOR PHASE II BLADE FORGING

IV. CONE DEFORMATION PROCESSING DEVELOPMENT

A. Background

The program redirection was initiated to satisfy potential applications for beryllium cone forgings. Future needs had encompassed a wide variety of conical shapes. Ultimate uses included jet engine and aerospace programs in size ranges up to four feet in diameter to over 100 inches long. Substantial quantities may be required extending to many hundreds of pieces. Beryllium conical frustums have been forged into relatively thick-walled configurations having a height-to-diameter ratio of less than one. This program was directed toward the production of thinner-walled cones having a height-to-diameter ratio greater than one. The basic technique consists of a controlled deformation process to produce a hollow right cylinder and converting the hollow cylinder into a cone using forming techniques.

The two major objectives of Phase III of this program were:

1. Investigation of forging parameters for the manufacture of a series of beryllium cones having various crystallographic textures to provide a range of mechanical property values at a yield strength level in excess of 65 Ksi.

2. Development of techniques for forming cones with improved material utilization.

The planned program entailed manufacture of a series of cones using different forging sequences for developing a variety of crystallographic structures which can be used to program the manufacture of cones for applications having various requirements. The appropriate forging sequence can be selected to meet specific mechanical property requirements of individual programs. Greatest emphasis had been placed upon development of optimum mechanical properties in two directions (axial and circumferential). It was planned that a series of structures be developed aiming toward an optimum structure which would have high, balanced mechanical properties in two directions without a high degree of preferred orientation.

The forming concept used was tailored for beryllium and is, in part, an extension of blocking procedures used for forging beryllium parts. Experience did not exist, however, for the use of filler materials inside a hollow cylinder for forming beryllium cones. The concept appeared particularly attractive for forming thin-walled conical shapes. The procedure can be varied to permit forming both open-ended and closed cylinders and has the potential for maintaining, reducing, or increasing wall thickness during forming. All of the possible variations of the process were not attempted under this program. However, sufficient background was established to permit more rapid development of specific conical shapes for future needs.

B. Material Procurement and Allocation

The material selected for this evaluation was Type 4 beryllium, vacuum-hot-pressed from virgin powder as described earlier in this report. This grade of beryllium reproducibly demonstrated superior forgeability and mechanical properties in Phase I of this Contract. Seven billets of this material were procured from The Brush Beryllium Company to Ladish Specification B102B. Because of the billet quantity and various configurations, it was necessary for the vendor to prepare two vacuum-hot-pressings to fulfill the Contract material requirements. Both of these pressings were prepared from the same master powder lot. This was a Contract requirement to minimize the material variables in the forging billets. The billet allocation is presented in Table XV.

TABLE XV

PHASE III BERYLLIUM BILLET ALLOCATION

FORGING SEQUENCE NO.	BILLET SIZE (INCHES)	VENDOR HOT-PRESSING IDENTITY
1	8-3/8 diameter x 4-7/16 long	4100
2	8-3/8 diameter x 5-15/16 long	4099
3	4 diameter x 22 long	4099
4	4 diameter x 26 long	4100
5	4 RCS x 17-1/2 long	4099
6	10-3/4 diameter x 15 long	4099
7	10-3/4 diameter x 15 long	4099
8	10-3/4 diameter x 15 long	4099
9	9-3/8 diameter x 13 long	4100
10	9-3/8 diameter x 13 long	4100

Forging Sequences 6 through 10 included a forward-extrusion operation at two reductions, which were performed on multiples for better material utilization.

1. Material Composition and Tensile Properties

Powder particle size distribution was specified as 98 per cent minus 20 micron. The actual powder particle size distribution is shown in Table XVI. The powder lot chemistry, vacuum-hot-pressed block chemistries, and tensile properties of each pressing are presented in Tables XVII and XVIII. The data presented in Tables XV through XVIII was furnished by The Brush Beryllium Company.

The analyses revealed that the two vacuum-hot-pressings were very similar. The only difference was the oxide content, which was within the variation of the determination method. An increase of 0.5 per cent in beryllium oxide content over the beryllium powder chemistry was noted.

TABLE XVI

BERYLLIUM POWDER MICROSIEVE ANALYSIS

PARTICLE SIZE (MICRONS)	PERCENTAGE
Minus 5	26.3
Minus 10	71.0
Minus 15	93.0
Minus 20	98.1
Minus 30	99.8

TABLE XVII

CHEMICAL COMPOSITION OF MASTER BERYLLIUM POWDER LOT AND VACUUM-HOT-PRESSED BLOCK CONSOLIDATED FROM THE POWDER

ELEMENT	PERCENTAGES		
	MASTER POWDER LOT	VACUUM-HOT-PRESSING NO. 4099	VACUUM-HOT-PRESSING NO. 4100
Beryllium	96.6	97.3	96.6
Beryllium Oxide	3.78	4.20	4.35
Carbon	0.09	0.12	0.11
Aluminum	0.03	0.03	0.03
Chromium	0.01	0.01	0.01
Iron	0.10	0.09	0.09
Magnesium	0.02	0.01	0.01
Manganese	0.01	0.01	0.01
Nickel	0.01	0.01	0.01
Titanium	0.01	0.01	0.01
Silver	0.0004	0.0004	0.0003
Calcium	0.01	0.01	0.01
Cobalt	0.0004	0.0003	0.0004
Copper	0.003	0.004	0.003
Molybdenum	0.001	0.001	0.001
Lead	0.001	*	*
Silicon	0.01	0.02	0.02
Zinc	0.005	0.005	0.005

* Not reported.

TABLE XVIII

ROOM-TEMPERATURE TENSILE PROPERTIES OF BERYLLIUM LOT NOS. 4099 AND 4100

VENDOR IDENTITY	TEST DIRECTION	0.2 PER CENT YIELD STRENGTH (KSI)	ULTIMATE STRENGTH (KSI)	ELONGATION (PER CENT)
4099	Longitudinal	54.8	72.2	1.5
4099	Transverse	58.0	79.9	3.0
4100	Longitudinal	55.7	71.7	1.6
4100	Transverse	57.3	77.8	3.2

A review of beryllium material evaluated indicated a marked increase in oxide for the Type 4 beryllium from 1.9 in Phase I to 4.3 per cent. One material difference that accounted in part for the higher oxide concentration was the finer powder particle size distribution for the Phase III material, which was 98 per cent minus 20 micron, as compared to 98 per cent minus 30 micron for the Phase I material.

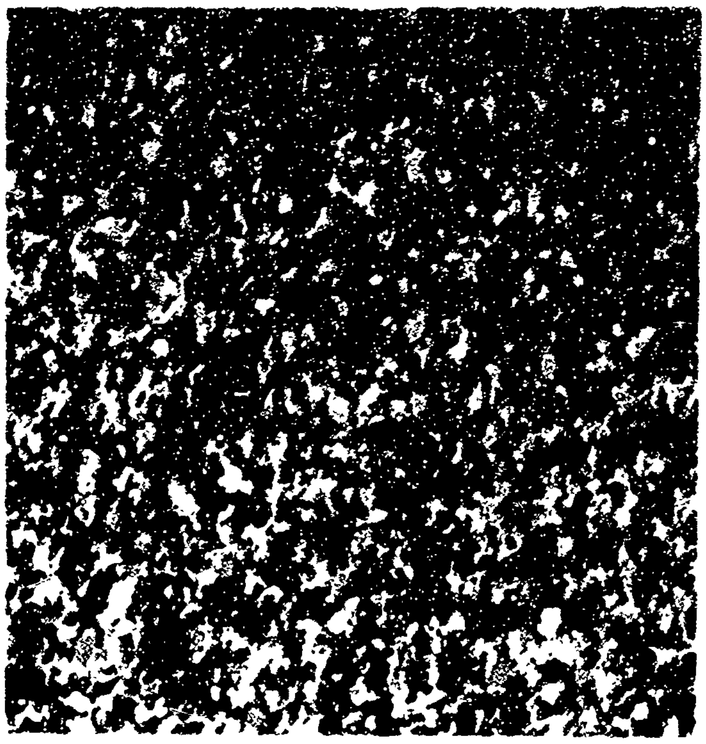
2. Metallographic Surveys

A metallographic survey of each vacuum-hot-pressing was conducted to determine material uniformity within each pressing and between pressings. These specimens were also examined for the presence of porosity and segregation.

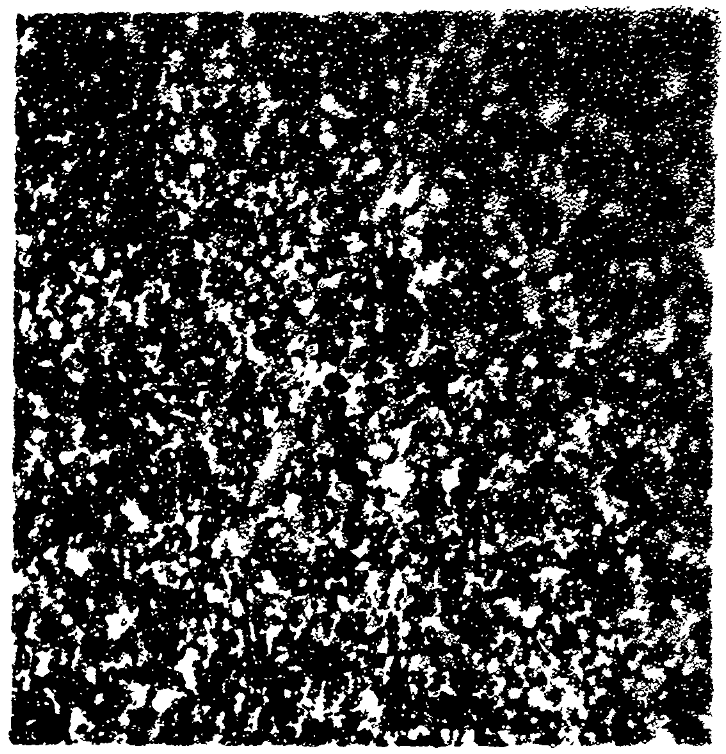
Representative structures from several locations within each vacuum-hot-pressing are illustrated in Figures 30 and 31. Generally, the structures for both pressings depicted a fine, uniform grain size without porosity or severe segregation. However, some isolated, coarse-grained areas were evident in specimens from the outer diameter of Pressing No. 4100, indicating some powder particle segregation. The metallographic differences appeared insignificant and would not distort the primary objective of this phase of the program, which was forging process evaluation.

3. Forgeability Determinations

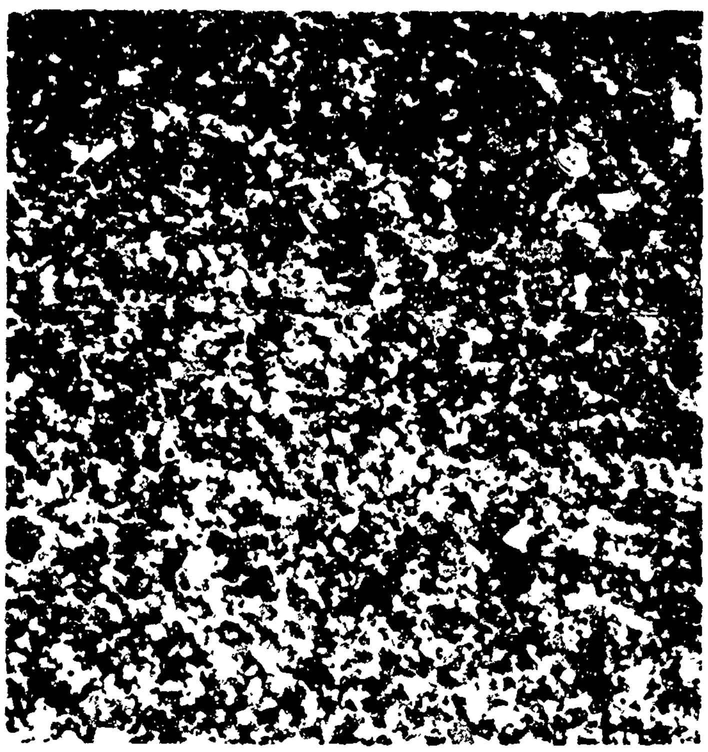
Three samples, each two-inch-diameter by two inches high, were procured from each Phase III pressing for forgeability determinations. The Ladish Beryllium Forgeability Test, which is described in the Appendix, was performed at a forging temperature of 1400°F. The results are presented in Table XIX.



Micro No. F-212
Center-Bottom of
Vacuum-Hot-Pressing



Micro No. F-213
Mid-radius-Bottom of
Vacuum-Hot-Pressing

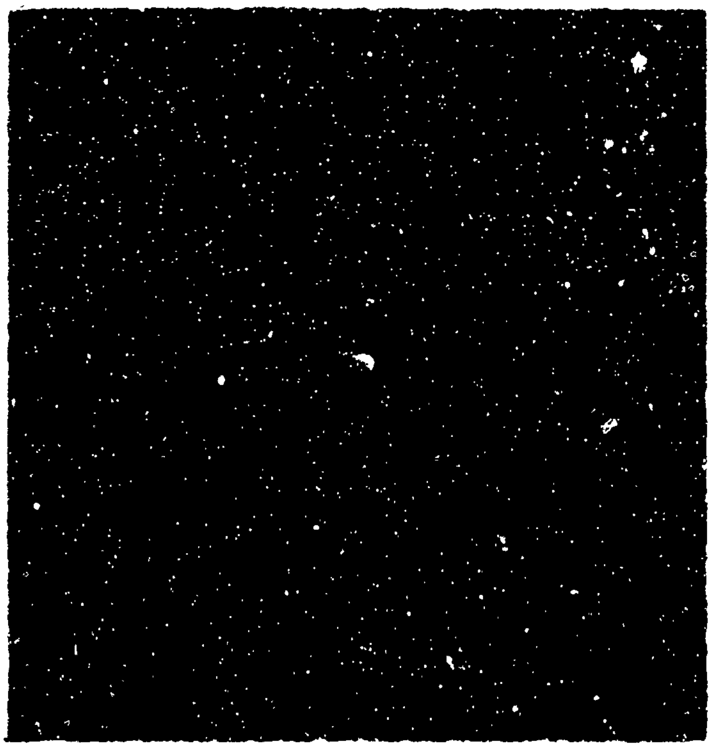


Micro No. F-214
Center-Top of
Vacuum-Hot-Pressing

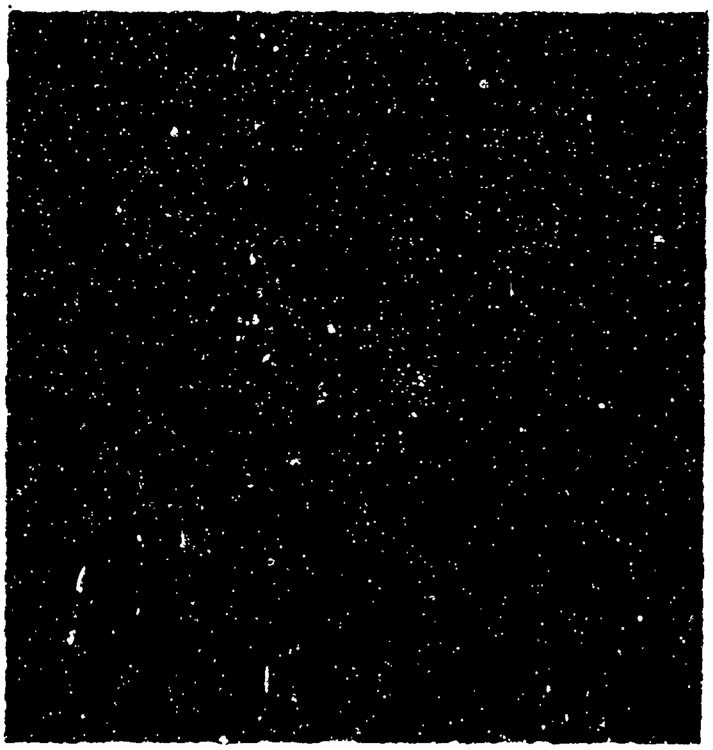
Micro No. F-215
Outer Diameter-Top of
Vacuum-Hot-Pressing

FIGURE 30

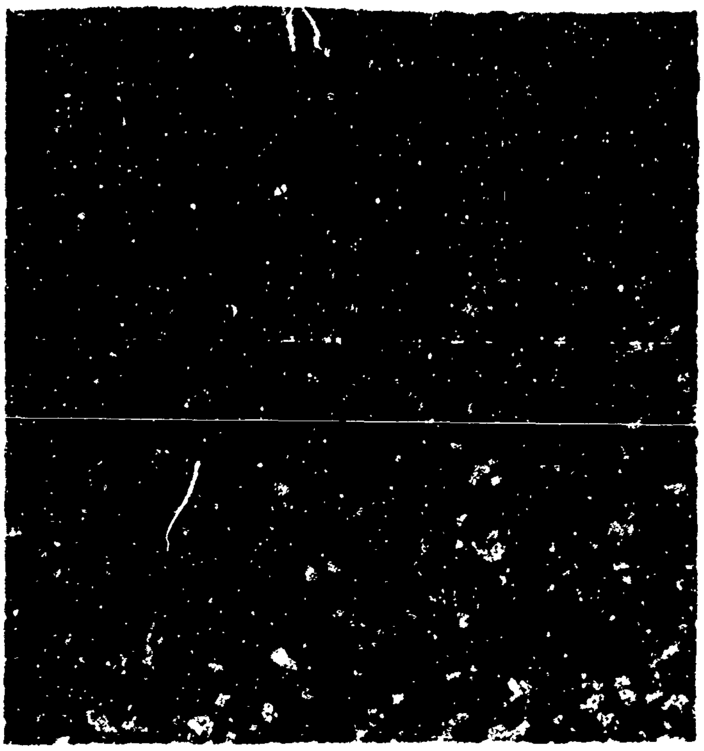
METALLOGRAPHIC SURVEY OF BRUSH BERYLLIUM
VACUUM-HOT-PRESSING NO. 4099
(Polarized Light -- 200X Magnification)



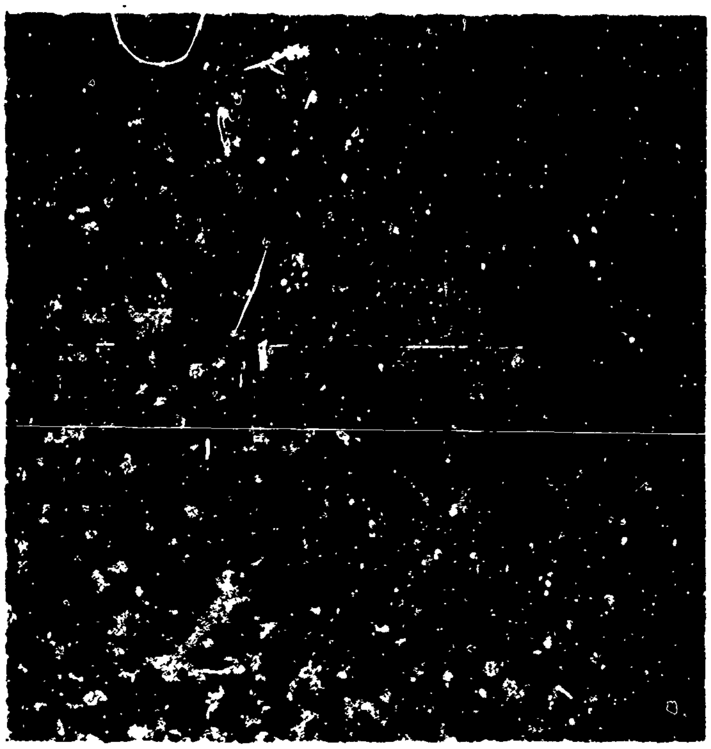
Micro No. F-216
Center-Bottom of
Vacuum-Hot-Pressing



Micro No. F-218
Outer Diameter-Bottom of
Vacuum-Hot-Pressing



Micro No. F-219
Center-Top of
Vacuum-Hot-Pressing



Micro No. F-220
Outer Diameter-Top of
Vacuum-Hot-Pressing

FIGURE 31

METALLOGRAPHIC SURVEY OF BRUSH BERYLLIUM
VACUUM-HOT-PRESSING NO. 4100
(Polarized Light -- 200X Magnification)

TABLE XIX

FORGEABILITY INDEX VALUES FOR PHASE III MATERIAL
UPSET-FORGED 60 PER CENT AT 1400°F

VACUUM-HOT-PRESSING IDENTITY	LOCATION WITHIN THE VACUUM-HOT-PRESSING	FORGEABILITY INDEX (PER CENT)
4099	Center - Top	68
4099	Center - Top	66
4099	Center - Top	65
4100	Mid-radius - Top	62
4100	Mid-radius - Top	66
4100	Mid-radius - Center	62

4. Non-Destructive Inspection

Non-destructive inspection of the billets by macroetch, dye-penetrant, radiographic, and ultrasonic techniques revealed that four of the billets deviated from the required levels of cleanliness and integrity: small surface cracks were apparent in two billets, and radiographic inclusions beyond the Ladish specification limit were present in one of these two and in two additional billets. Conditions such as cracking and inclusion "clouds" have had a detrimental effect upon a material's forgeability. In the past, beryllium billet failures during forging have been associated with these conditions. As a result, the billets that revealed these conditions were replaced with material available from the other pressing (No. 4100), which did not show any evidence of bands of inclusions or cracking. The other two billets were discrepant because of radiographic inclusions, and the material vendor agreed to guarantee the forgeability of these billets against failure associated with high-density radiographic inclusions.

Density determinations conducted on those billets whose size was within the limitations of the Contractor's equipment were satisfactory.

C. Engineering Analysis of Die Design Parameters for the Forming Operation

Die design parameters for forward extruding, back extruding, and upset-forging had been established prior to this program. Experience with forming conical beryllium shapes had been limited. In order to establish the forming process parameters, a model study was undertaken. This investigation consisted of the following four forging trials:

1. Technique survey;
2. Development of a preferred preform shape;
3. Survey of beryllium forming techniques;
4. Beryllium forming technique verification.

1. Technique Survey

Identical cup-shaped preforms were machined from solid carbon steel blocks for these trials. The forging die used is illustrated in Figure 32. The conditions investigated included carbon steel and sand fillers, a cup-shaped preform without a filler, and a contoured carbon steel filler. The preform shapes and the conical forgings produced are shown in Figure 33.

Evaluation of the trials and results showed the following:

a. The non-uniform wall, produced in each conical forging, was associated with the slug configuration.

b. The carbon steel fillers produced a significant reduction in the extrusion wall.

c. When no filler material was used, the wall upset, and a much shorter conical shape was produced.

d. The sand filler was so compressible that the shape produced was similar to that formed without a filler material.

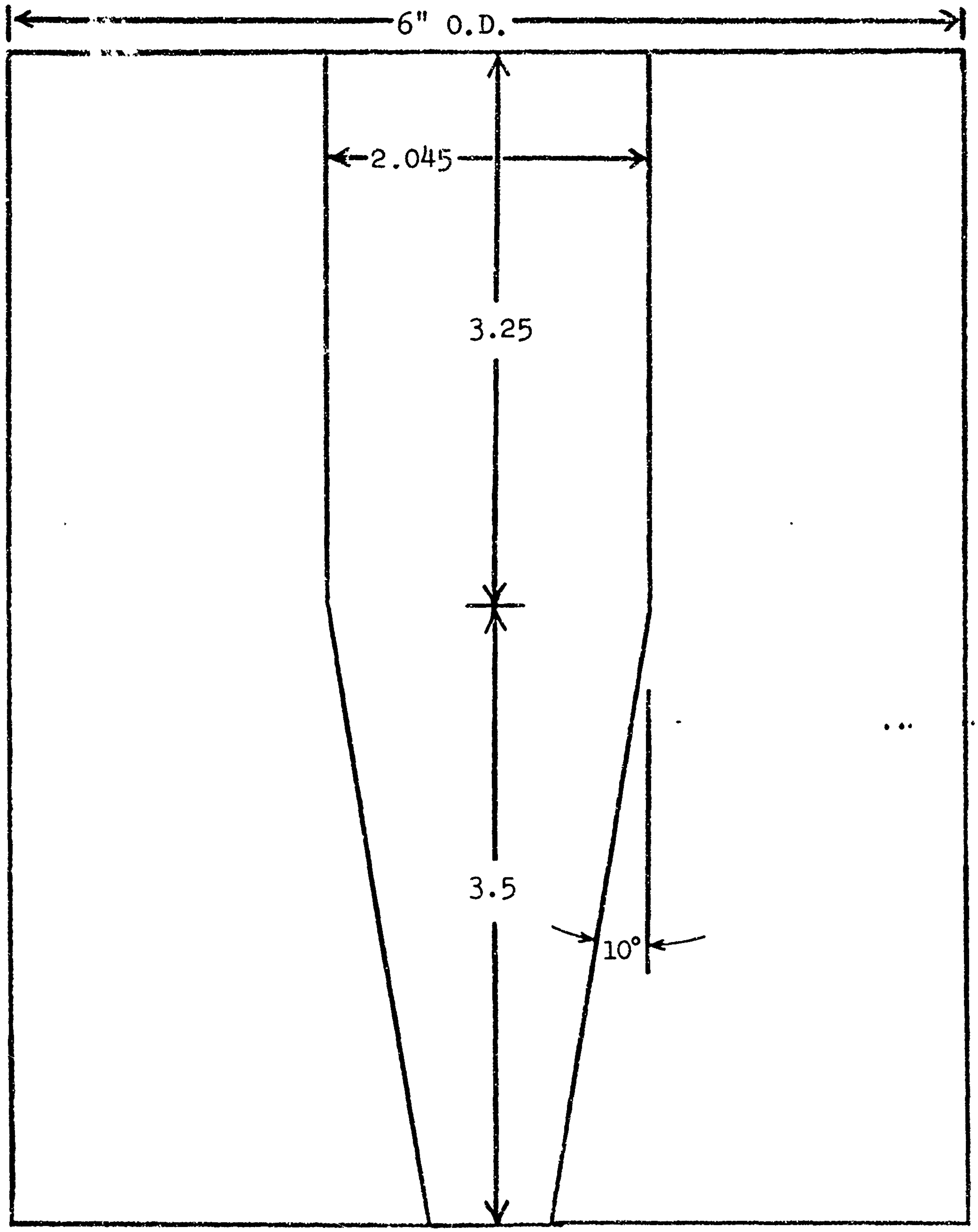
e. The contoured filler produced a conical shape similar to that produced from use of a solid carbon steel filler.

2. Development of the Preform Shape

The objective of the second portion of the model study was to obtain a more uniform wall in the conical configuration. The cylinder shape was redesigned to investigate the effects of larger radii, different slug thicknesses, and a chamfer upon the forming of the conical configuration. The revised preform shapes and the conical configurations produced are illustrated in Figure 34. Filler material was not used. The preform shape with large radii and a slug thickness equal to the preform wall thickness produced the most uniform conical forging.

3. Survey of Beryllium Forming Techniques

The objectives of this part of the investigation were evaluation of effects of different filler materials, use of restraint on the beryllium during forming, and elimination of wall upsetting. Four beryllium cylinders were machined into the preform shape previously developed. Two of these preforms were formed without using filler material. The two other preforms employed fillers of Type 304 Stainless Steel and solid graphite, respectively. A stainless contoured cap was prepared for each of the four pieces



(All dimensions in inches.)

FIGURE 32

SCHEMATIC OF THE FORMING DIE EMPLOYED IN THE ENGINEERING ANALYSIS OF THE DIE DESIGN PARAMETERS FOR THE FORMING OPERATION

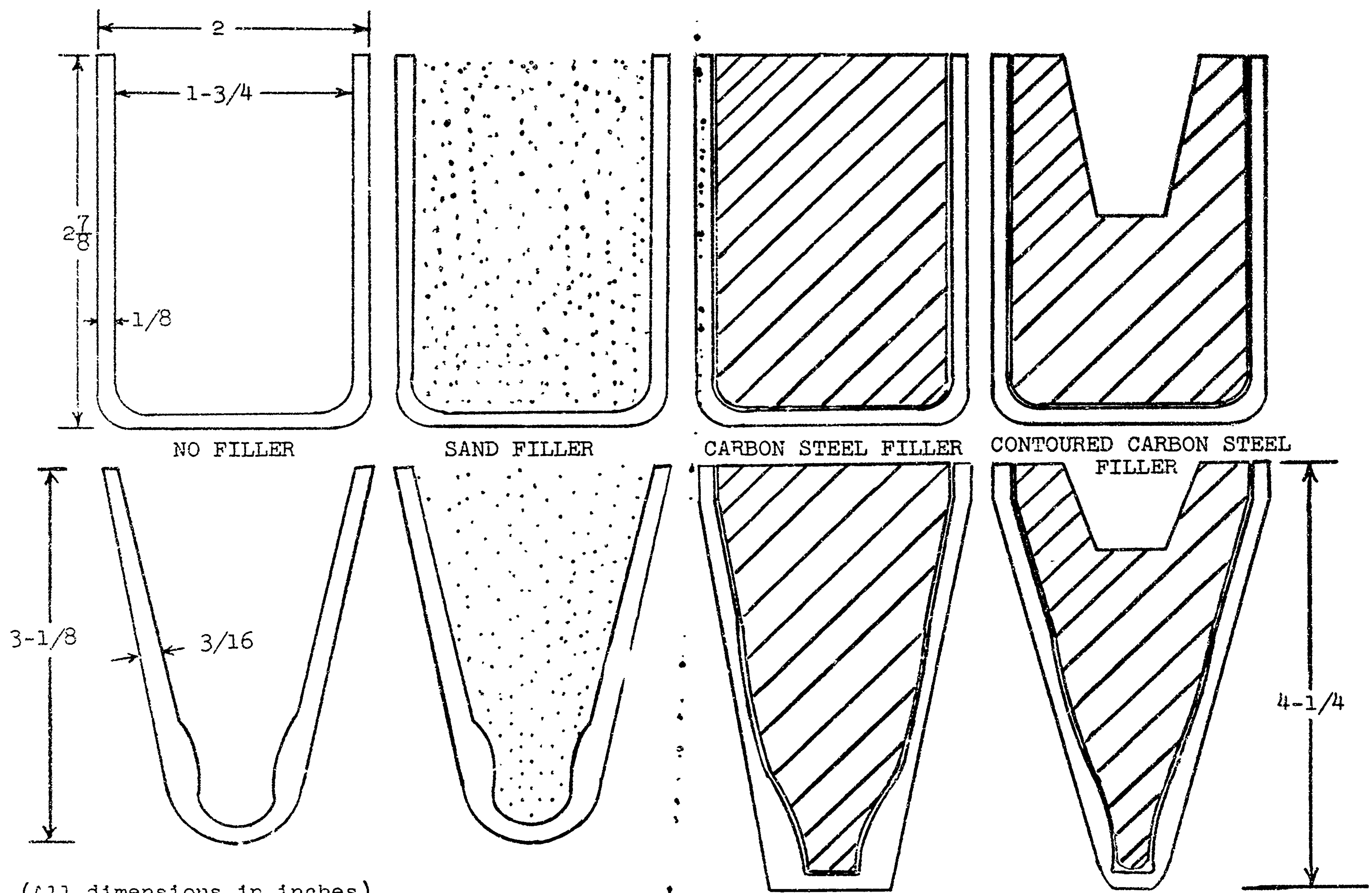
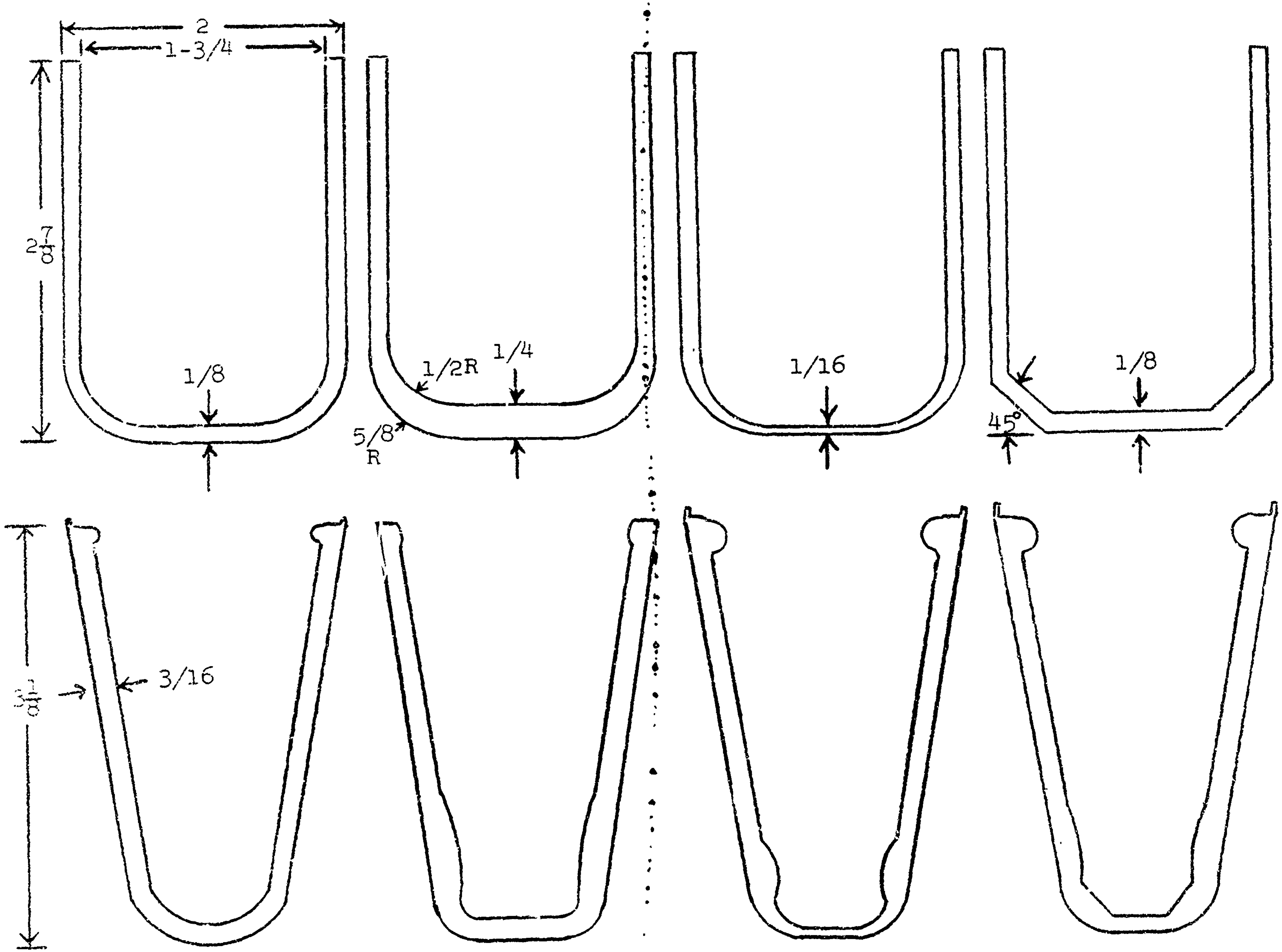


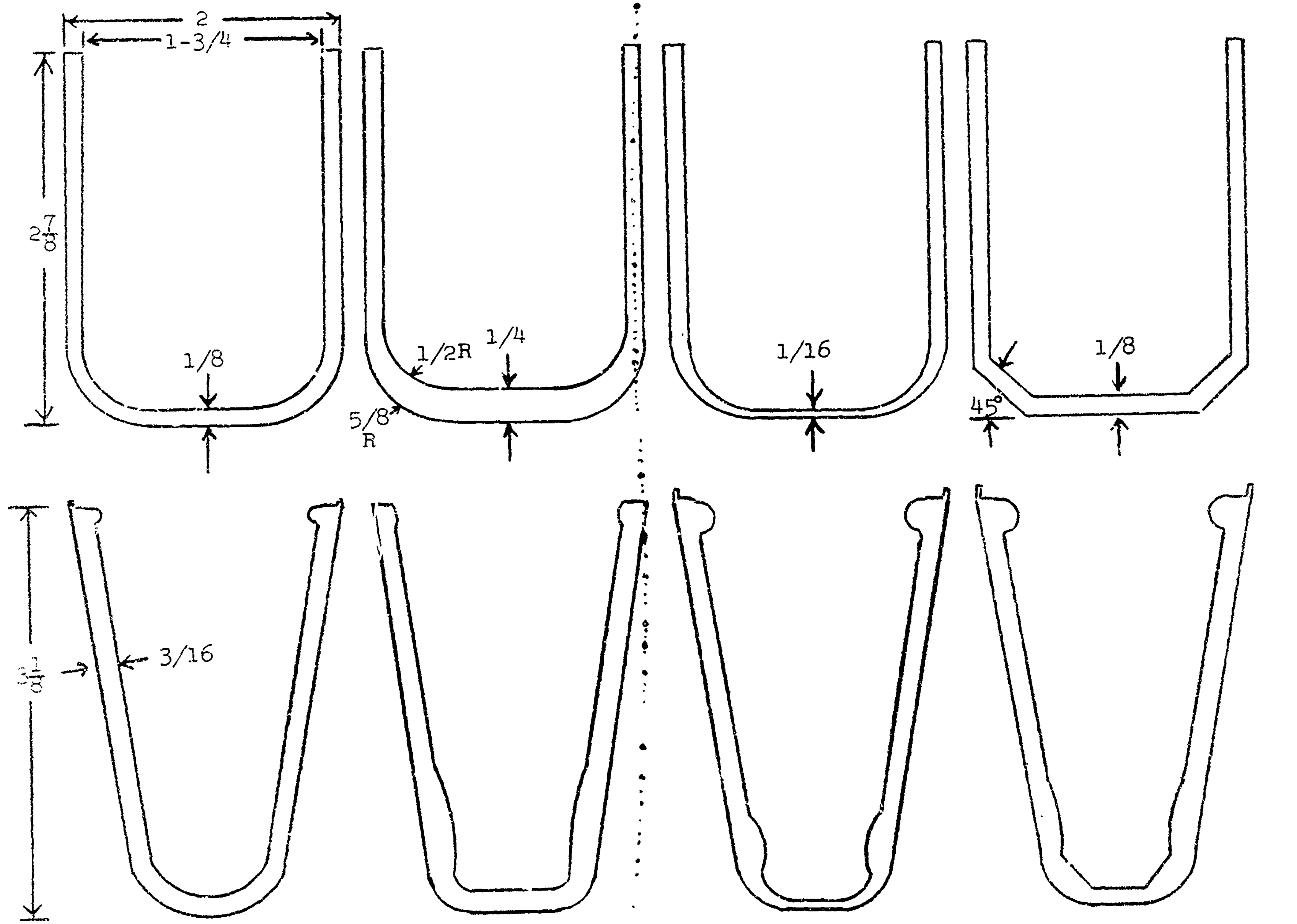
FIGURE 33

CARBON STEEL PREFORM SHAPES AND RESULTING CONICAL CONFIGURATIONS PRODUCED IN THE TECHNIQUE SURVEY



(All dimensions in inches.)

FIGURE 34. CARBON STEEL PREFORM SHAPES AND RESULTING CONICAL CONFIGURATIONS PRODUCED



(All dimensions in inches.)

FIGURE 34. CARBON STEEL PREFORM SHAPES AND RESULTING CONICAL CONFIGURATIONS PRODUCED TO EVALUATE THE PREFORM SHAPES.

to prevent upsetting in the cone rim. The caps were heated to 1200°F with each beryllium preform shape. One of the hollow (unfilled) preforms was formed using back pressure in the forming die. The die was sealed with a carbon steel cap and the conical section of the die cavity was filled with lubricant. The other three beryllium preforms did not employ restraint. The four cylinders and the conical beryllium forgings produced are illustrated in Figure 35.

Analysis of this trial is as follows:

a. The stainless steel cap reduced the upsetting in the open ends of the conical shapes.

b. The restraint technique was unsuccessful. Use of restraint remained to be evaluated.

c. The beryllium cylinder formed without use of filler material or restraint produced a defect-free conical frustum. This forging did not fill the die cavity because of the uniform upsetting in the wall during forming.

d. The beryllium cylinder formed using graphite filler material produced a forging with only slight defects on the nose of the conical shape. The graphite was compressed, but it still provided enough restraint to maintain the wall thickness of the preform without any visible upsetting or wall reduction. Thus, an increase in height was noted when compared to the beryllium shapes formed without filler materials.

e. When the stainless steel filler was used, a reduction in the beryllium preform wall was experienced. The resistance of the stainless steel to plastic deformation imparted during forming was greater than the resistance of the beryllium. As a result, a void between the beryllium and the stainless steel was created.

4. Beryllium Forming Technique Verification

In the previous trials, the most successful techniques used either a graphite filler or no filler at all. Dimensional control was the problem encountered with both of these techniques. For both conditions (compressible graphite filler or no filler material) a volumetric relationship did not exist between the preform shape and the formed conical configuration. In an attempt to verify differences between the two techniques, the height of the beryllium preform shapes was varied by one-fourth inch. The beryllium preforms and the configurations produced in forming are illustrated in Figure 36. The cylinder formed without use of filler material produced another sound, conical forging. The heights of the two frustums produced were equal, although the height of

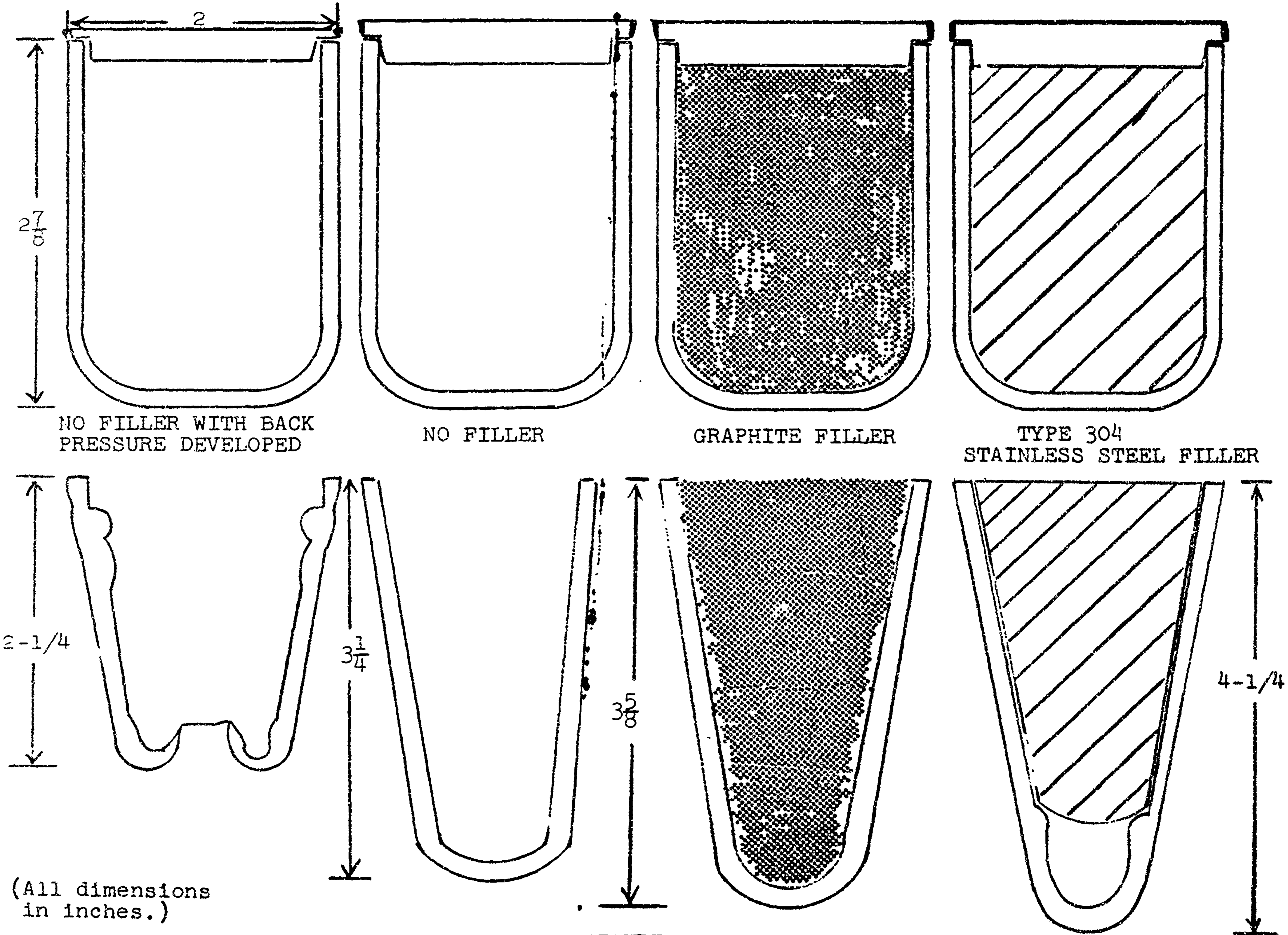
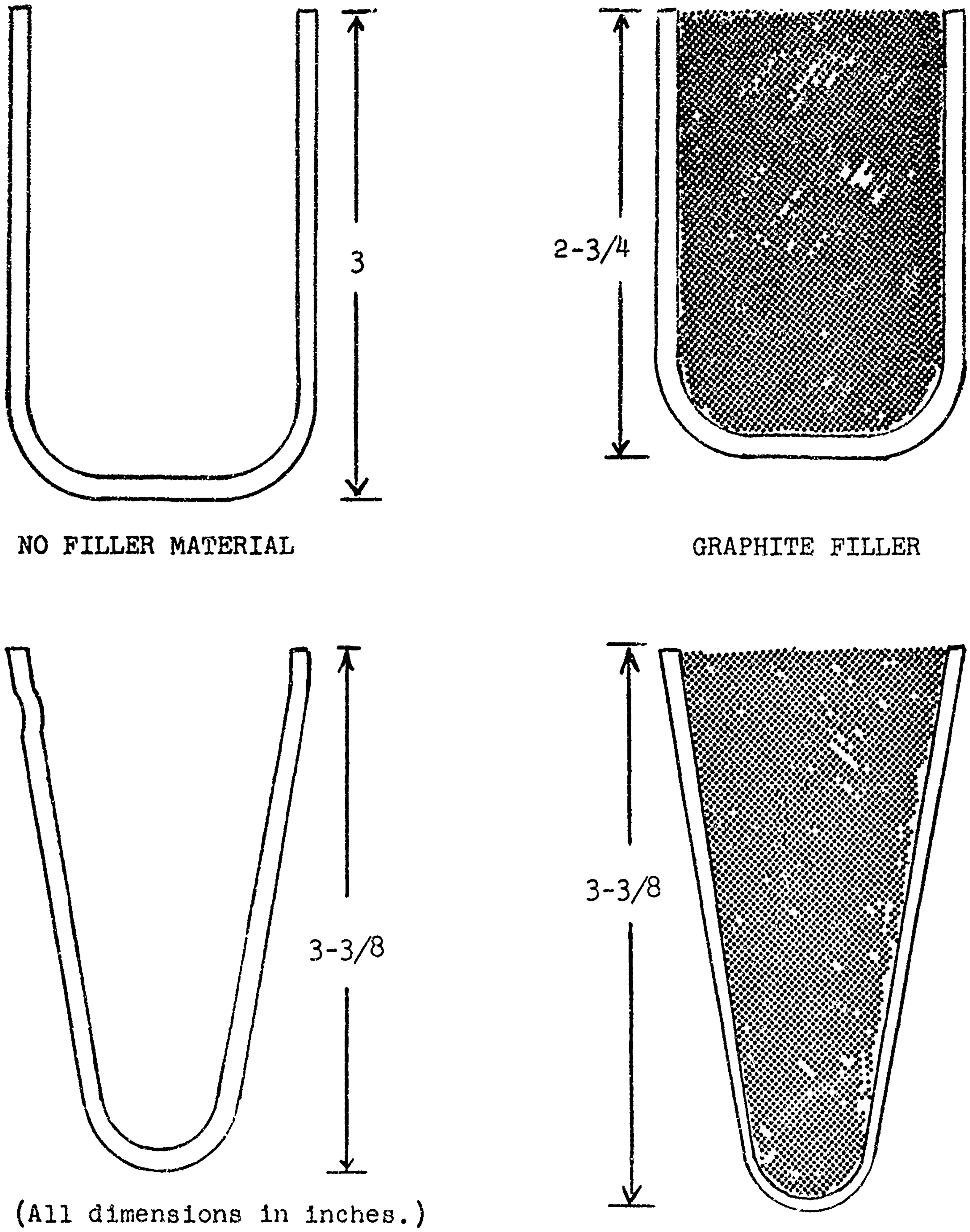


FIGURE 35

BERYLLIUM PREFORM SHAPES AND CONICAL CONFIGURATIONS PRODUCED IN THE FORMING



(All dimensions in inches.)

FIGURE 36

BERYLLIUM PREFORM SHAPES AND CONICAL CONFIGURATIONS
PRODUCED IN THE FORMING PROCESS VERIFICATION

the graphite-filled starting preform was one-fourth inch less than the unfilled preform.

Two additional beryllium preforms were machined. Based upon prior forging trials, modifications were incorporated into the forming process. The stainless steel cap was eliminated. The contour of the cap was machined into the forming punch. During forming, the first piece failed catastrophically. The failure was associated with the high pressures developed during the press ram stroke. This condition was corrected and a sound conical beryllium forging was produced to the anticipated dimensions. This forging is illustrated in Figure 37 with the preform shape.

Based upon the results of this model study, the following parameters were selected for forming the subscale 8-1/4-inch-diameter frustums:

a. A contour punch was used to eliminate upsetting in the open end of the conical beryllium configuration.

b. A beryllium preform shape having large radii and a slug thickness equal to the wall thickness and a graphite filler was selected as the most flexible and practical process for forging conical beryllium configurations.

c. A beryllium forging temperature of 1200°F and a die temperature of 800°F minimum was initially used since these temperatures produced satisfactory cones.

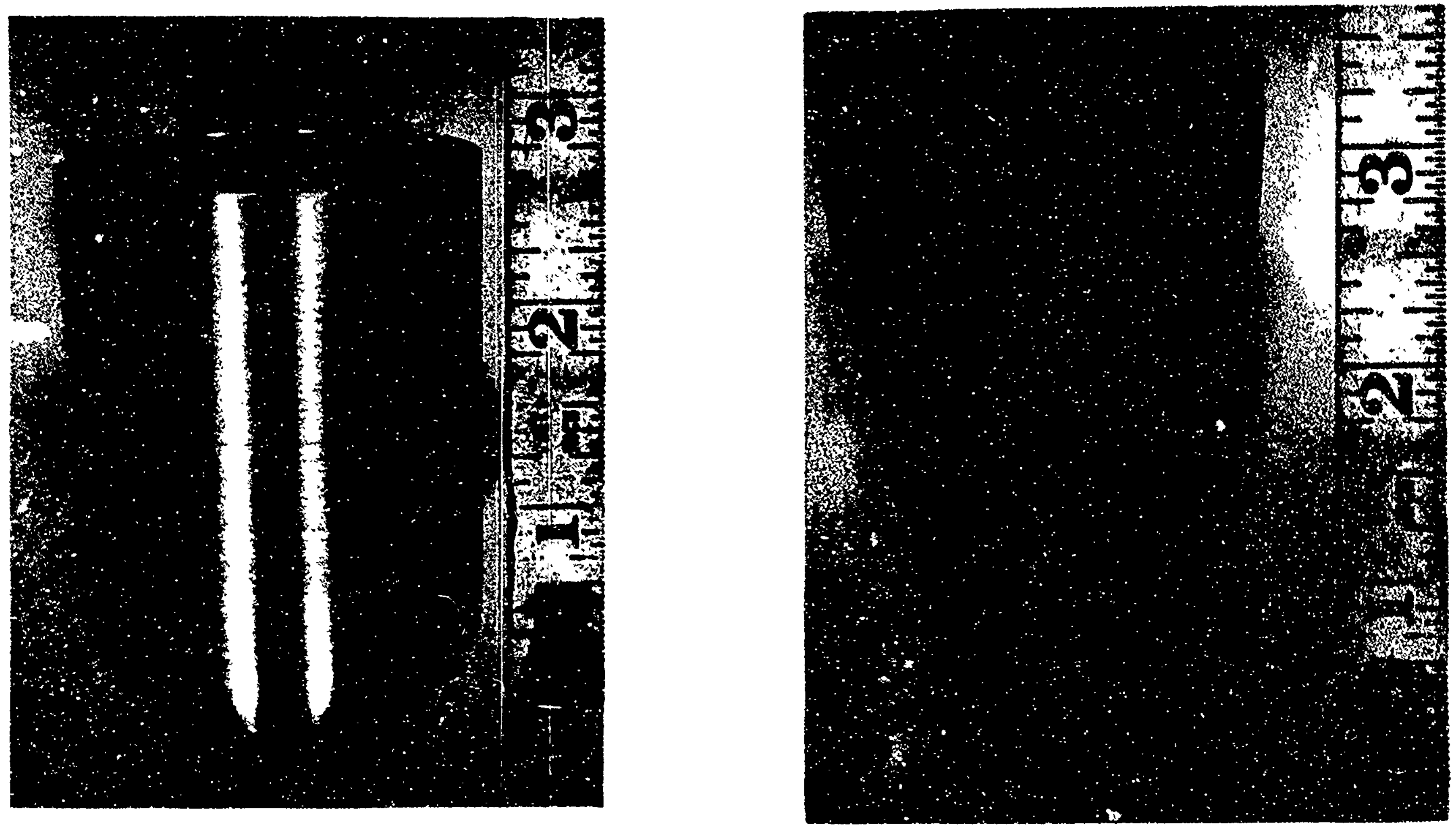


FIGURE 37

BACK-EXTRUDED, MACHINED BERYLLIUM PREFORM SHAPE (LEFT) AND RESULTANT FORMED CONICAL CONFIGURATION

D. Subscale Cone Development

The objective of Phase III of this Contract was to fabricate and evaluate subscale conical beryllium forgings. Ten manufacturing sequences were employed utilizing different reductions and different combinations of forward-extrusion, upset-forging, and back-extrusion. The ten selected sequences and reductions for each sequence are outlined in Table XX and are shown schematically in Figure 38. For the first five sequences, individual forging billets were procured. However, only two billets were procured for the five sequences which employ a forward-extrusion operation. The extrusions were sectioned to provide five billets which were processed in Sequences 6 through 10. By extruding multiples rather than individual billets, typical extrusion losses were reduced.

1. Forward-Extrusion Operations

The billets designated Serials 6 and 9 were scheduled for extrusion at ratios of four-to-one and three-to-one, respectively. The beryllium billets were encapsulated in 1/4-inch-thick carbon steel (SAE-1010 Grade). A forging temperature of 1400°F was selected because the Contractor's experience indicated that, at that temperature and at lower extrusion ratios, good work penetration to the extrusion center resulted. Prior extrusion work at Ladish Co. showed an area of potential hazard at the butt end of the extrusion where the normal draw, or suck-in, occurs. This draw in beryllium acts as a nucleation site for axial cracks that propagate the full length of the extrusion. To circumvent this hazard, the extrusion operation was programed to prevent occurrence of the draw by holding back a portion of the un-extruded metal in the die orifice.

The extrusion operations for the two billets proceeded as planned. Forging parameters were as follows:

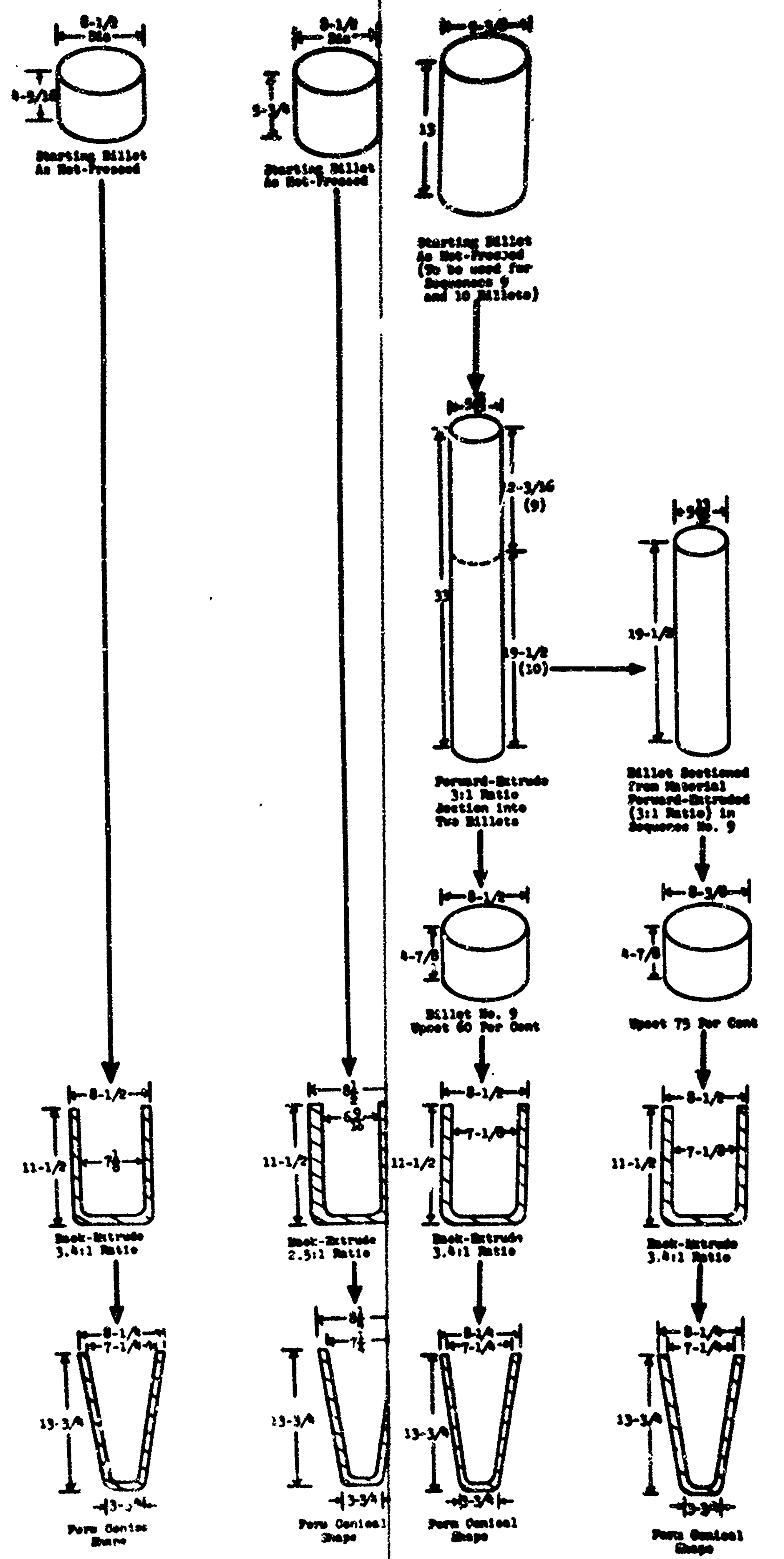
PARAMETER	SERIAL 6	SERIAL 9
Extrusion Ratio	4 to 1	3 to 1
Forging Temperature	1400°F	1400°F
Time Held at Temperature	One Hour	One Hour
Die Temperature	800°F	700°F
Forging Load	2850 Tons	1960 Tons
Finishing Temperature	1300°F	1300°F
Post-Forging Thermal Treatment	Stress-relieved at 1375°F for one hour; slow-cooled in insulating material to 150°F.	

Examination of the extrusions showed that the jacket material had deformed uniformly without cracking or exposing the beryllium. The two extrusions, shown in the photographs in Figures 39 and 40, were defect-free and fulfilled the dimensional requirements.

TABLE XX

MANUFACTURING SEQUENCES FOR PHASE III

SEQUENCE NO.	OPERATION	REDUCTION
1	Back Extrude Form	3.4 : 1
2	Back Extrude Form	2.5 : 1
3	Upset Back Extrude Form	80 per cent (5:1) 3.4 : 1
4	Upset Back Extrude Form	80 per cent (5:1) 2.5 : 1
5	Upset Back Extrude Form	75 per cent (4:1) 3.4 : 1
6	Forward Extrude Upset Back Extrude Form	4 : 1 60 per cent 3.4 : 1
7	Forward Extrude Upset Back Extrude Form	4 : 1 60 per cent 2.5 : 1
8	Forward Extrude Upset Back Extrude Form	4 : 1 75 per cent 3.4 : 1
9	Forward Extrude Upset Back Extrude Form	3 : 1 60 per cent 3.4 : 1
10	Forward Extrude Upset Back Extrude Form	3 : 1 75 per cent 3.4 : 1



SEQUENCE 1 SEQUENC SEQUENCE 9 SEQUENCE 10

FIG

PROGRAMMED SUB-SCALE
PHASE III BERYLLIU

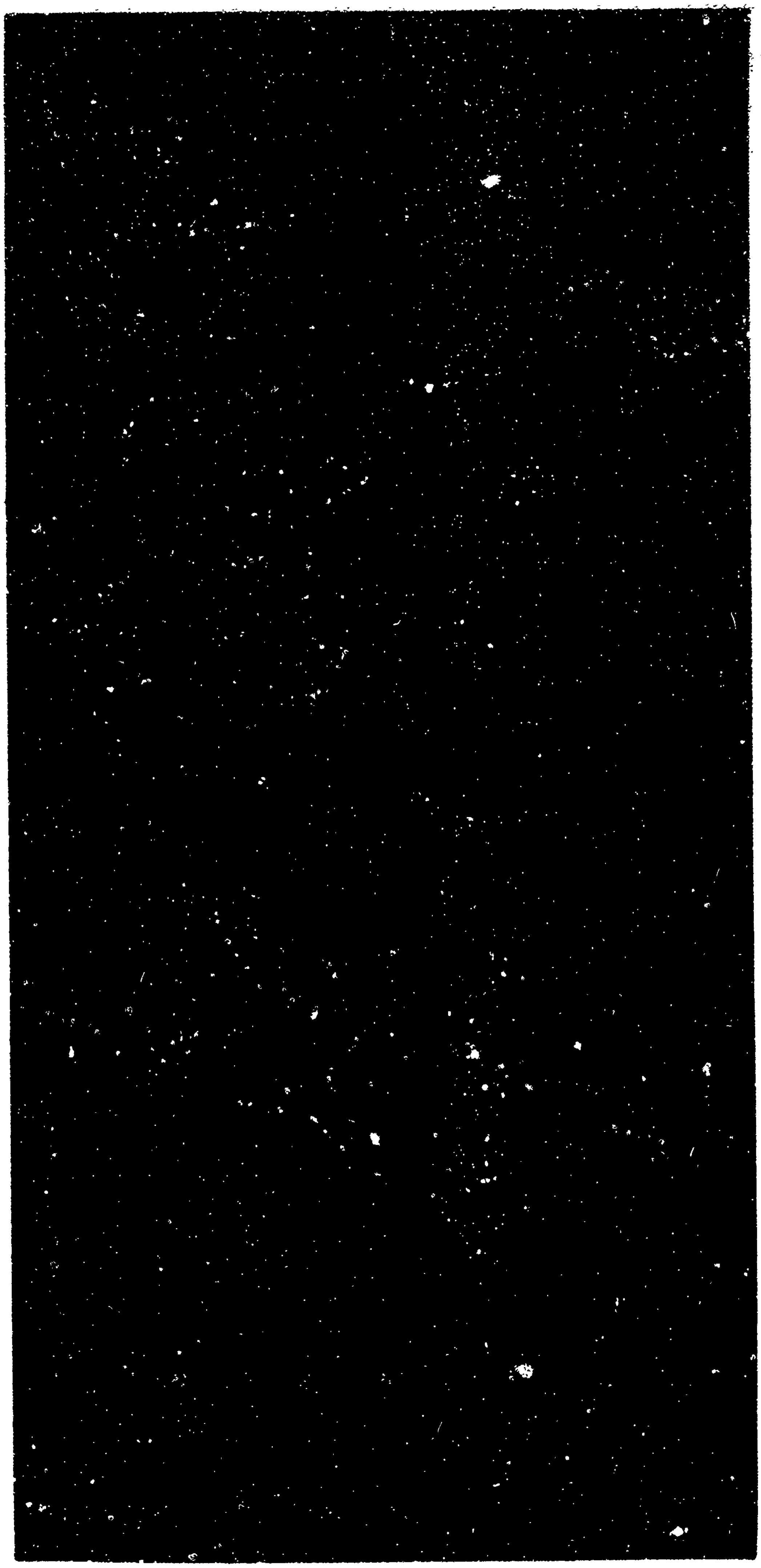


FIGURE 39: BILLET SERIAL 9 EXTRUDED AT 1400°F AT A RATIO OF 3:1. JACKETING REMOVED EXCEPT FOR BUTT END.

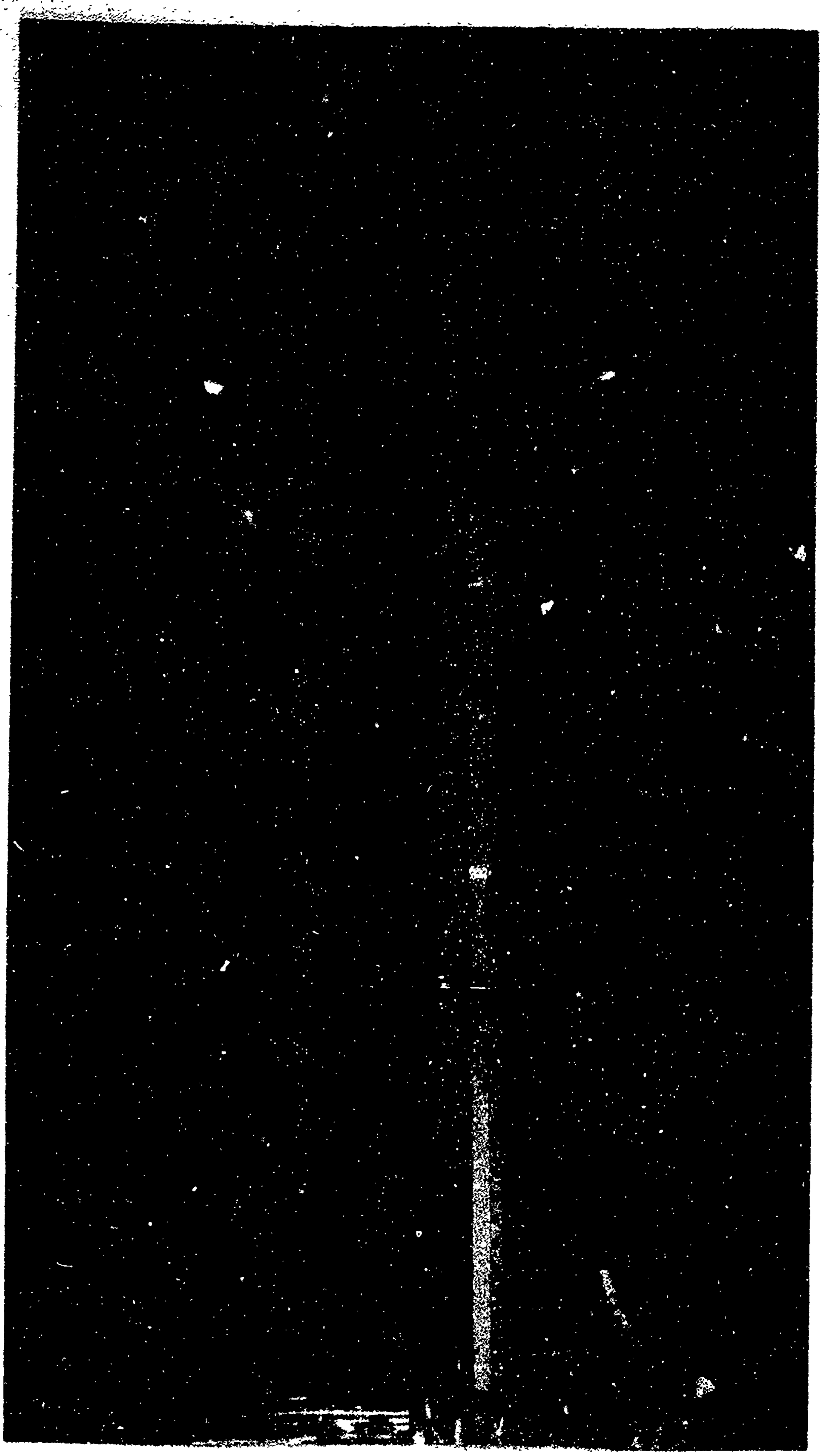


FIGURE 40: BILLET SERIAL 6 EXTRUDED AT 1400°F AT A RATIO OF 4:1. JACKETING MATERIAL IS COMPLETELY REMOVED.

Extrusion Serials 6 and 9 were subsequently sectioned to yield five billets for allocation to Sequences 6 through 10. Three billets, Serials 6, 7, and 8, were removed from Extrusion Serial 6, while Extrusion Serial 9 yielded the two billets for Sequences 9 and 10. The five billets at the various lengths are illustrated in Figure 41.

2. Summary of Upset-forging Operations

The technique utilized by the Contractor in upset-forging unclad beryllium maintains compressive restraint at the outer diameter of the billet by using a closed die. The upset reductions are imparted incrementally with intermediate stress-relieving cycles. After inspection, polishing is performed as required between upset-forging operations to remove stress concentration conditions such as superficial cracks, sharp corners, and rough surface areas. The presence of these conditions in a forging billet could result in complete loss of the billet because of the limited forgeability and crack-propagation characteristics of beryllium.

Three reductions were selected for evaluating upset-forging reductions upon mechanical and metallurgical properties of the conical configurations. The Contractor's technique for upset-forging beryllium required three to six operations to produce the selected reductions of 60, 75, and 80 per cent. A closed die was used for the final increments of upset-reduction for five billets to impart the required amount of reduction with maximum material utilization. The "bulge" which normally occurs during free upset-forging was thereby minimized. The billets are shown in Figure 42 for the two final upset-forging passes in the closed dies. Due to a difference of geometry and reduction relationships, Billets 8 and 10 were upset-forged between hot, flat dies without the need for outer-diameter restraint. Billets before and after upset-forging are shown in Figure 43. The excess material on the outer diameter (the bulge) of these two billets was used for mechanical property testing at this stage of processing. The results of the room-temperature tensile tests are shown in Table XXI for two test directions. A balance of ductility was developed in each billet. The forging parameters for the upset-forging passes are listed in Table XXII.

3. Back-Extrusion Operations

All billets were back-extruded at one of two extrusion ratios, i.e., 2.5-to-one or 3.4-to-one. These ratios were selected on the basis of the highest reduction attempted on beryllium within the Contractor's facilities during prior programs and on the improved material utilization which chould be derived from back-extruding at higher ratios. Several hundred beryllium forgings in the same approximate size range had been successfully back-extruded at the lower ratio. Use of the higher ratio was directed toward the economic manufacture of aerospace components which demand a

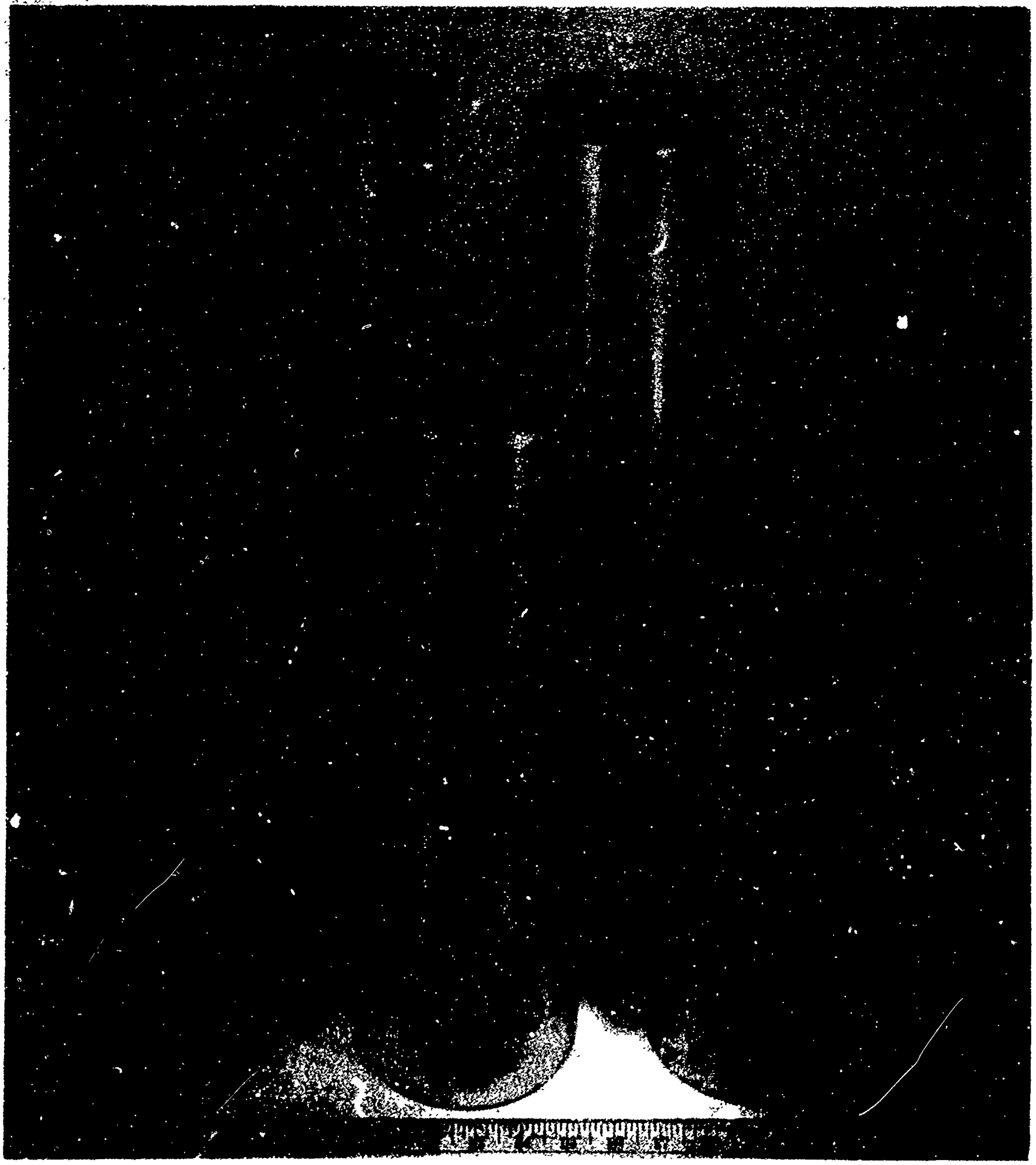
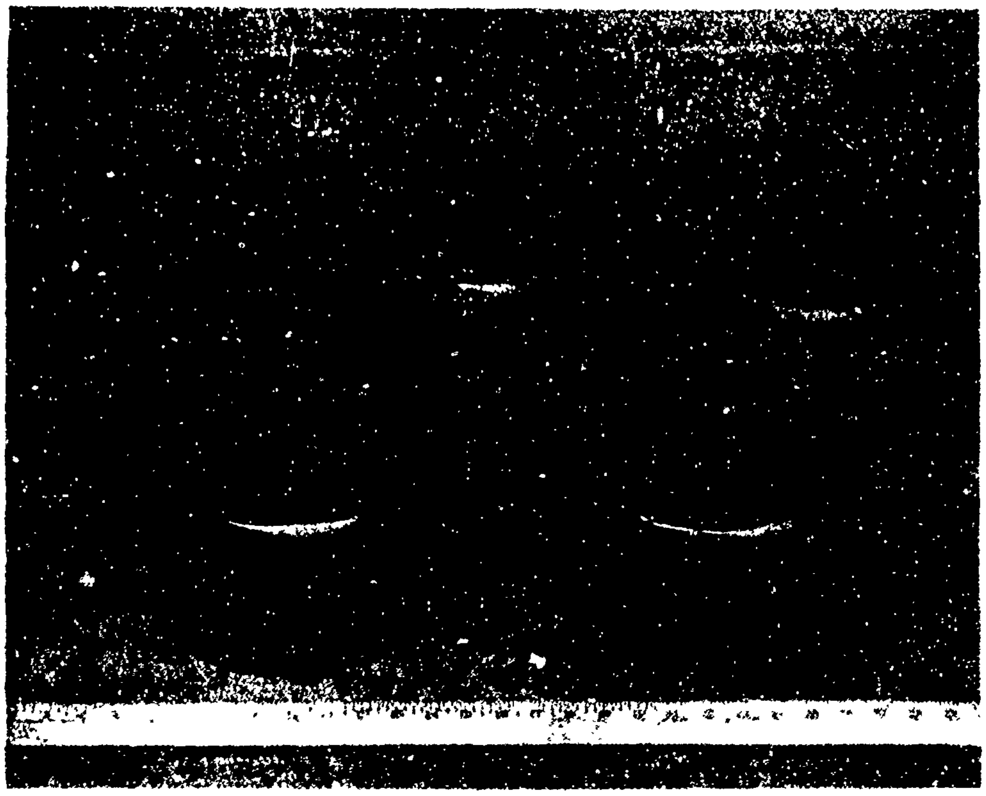


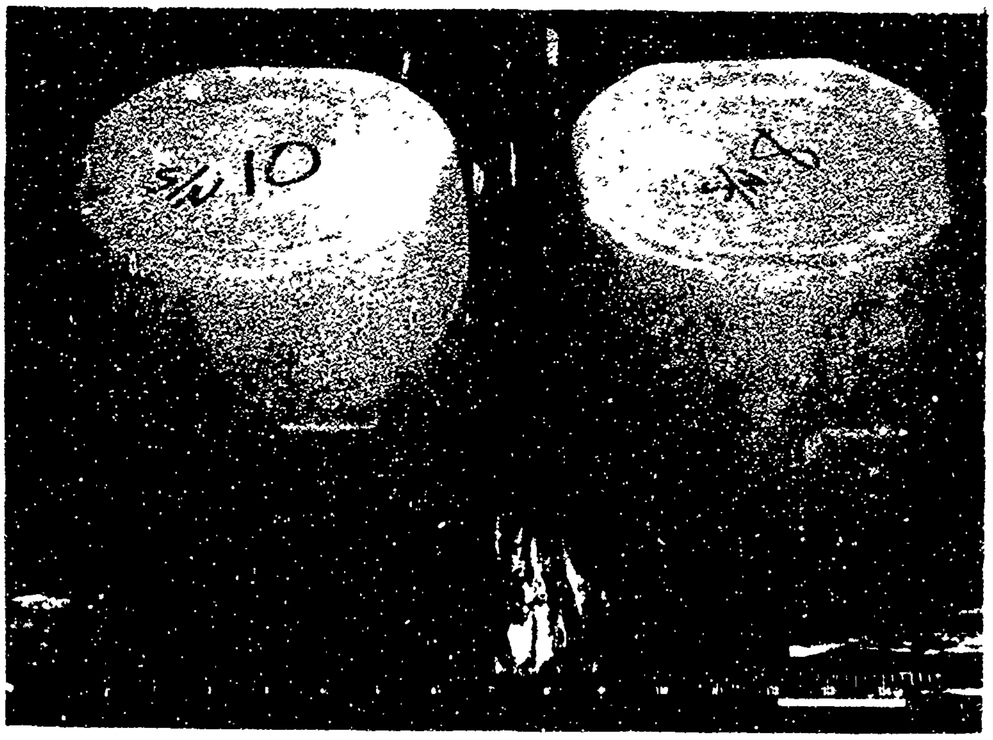
FIGURE 41: BILLETS YIELDED BY EXTRUSION SERIALS 6 (SERIALS 6, 7, AND 8 ABOVE) AND 9 (SERIALS 9 AND 10 ABOVE). PIECES ARE MACHINED TO LENGTHS REQUIRED FOR FORGING SEQUENCES 6 THROUGH 10.

BERYLLIUM BILLETS IDENTIFIED WITH SERIAL NUMBERS PRIOR TO THE RE-BLOCKING OPERATION



BILLET SERIALS IN THE AS-FORGED CONDITION AFTER COMPLETION OF SECOND BLOCKING OPERATION

FIGURE 42



BLOCKED SERIAL NOS. 8 AND 10 PRIOR TO FREE UPSETTING

SERIAL NOS. 8 AND 10 IN THE AS-FORGED CONDITION AFTER COMPLETION OF THE UPSETTING OPERATION

FIGURE 43

TABLE XXI

ROOM-TEMPERATURE SMOOTH TENSILE PROPERTIES OF BILLET SERIALS NO. 8 AND 10 AFTER EXTRUSION AT RATIOS OF 4:1 AND 3:1, RESPECTIVELY, AND UPSET REDUCTIONS OF 75 PER CENT

(All specimens tested were 0.125-inch diameter.)

BILLET SERIAL NO.	TEST DIRECTION	0.2 PER CENT YIELD STRENGTH (KSI)	ULTIMATE STRENGTH (KSI)	ELONGATION (PER CENT)	REDUCTION IN AREA (PER CENT)
8	Circumferential	75.2	89.7	4.5	6.3
8	Circumferential	77.3	92.2	5.7	7.0
8	Axial	72.9	87.0	2.2	4.0
8	Axial	57.0	86.5	3.2	3.4
10	Circumferential	71.9	85.1	2.6	4.7
10	Circumferential	68.8	86.6	4.7	4.7
10	Axial	70.0	84.0	3.6	5.5
10	Axial	69.1	81.7	2.4	4.0

TABLE XXII

SUMMARY OF UPSET-FORGING PARAMETERS

PARAMETER	UPSET-FORGING OPERATION						
	FIRST	SECOND	THIRD	FOURTH	FIFTH	SIXTH	FREE UPSETTING
Billets Involved	3 and 4	3 - 5	3 - 10	3 - 10	3 - 10	3, 4, 5, 6 and 9	8 and 10
Forging Temperature (°F)	1375	1375	1375	1375	1375	1350	1350
Time Held at Temperature (Minutes)	30 - 90	30 - 90	30 - 90	60 - 120	290-335	90-100	180
Die Temperature (°F)	800	800	800	700	750	800	1250
Forging Load (Tons)	600-800	600-1000	800-1000	800-1200	1200-1400	1400-1600	2000
Post-Forging Thermal Treatment	1350°F for one hour, and slow cooled.					1325°F for one hour, and slow cooled.	

thin-walled structural design. This higher ratio represented an extension of the technical capability for back-extruding beryllium.

The back-extrusion operation employed the hydrodynamic-compressive restraint technique developed under Air Force Contract AF33(600)-36795.[1] A hot, mild-steel cylinder provided the restraint necessary to minimize tensile forces during extrusion. The technique is shown schematically in Figure 44. The punch applies force to deform the beryllium, which, in turn, is forced against the hot compression ring, causing the hot steel ring to deform into the space between the parallel surfaces of the top and bottom dies as indicated.

Billet Serials 2, 4, and 7 were back-extruded at the 2.5-to-one ratio. The forging parameters used are shown in Tables XXIII and XXIV. Visual inspection immediately following forging revealed superficial tears on the outer diameters of Serials 4 and 7. Visual examination after cleaning showed the presence of defects on both the inner and outer diameters. The back-extrusion tears located on the outer diameter were not deep, and were removed during the programed machining operation. The most severe outer-diameter rupturing occurred in Serial 4, which had a preferred orientation of basal planes perpendicular to the direction of metal flow during extrusion as a result of the prior upset-forging operation. Serial 2, which received no prior forging, was free of outer-diameter defects. The peripheral surfaces of these billets are shown in Figure 45. All of these pieces had inner-diameter cracks, however. The appearance of the cracks (tight, smooth, deep, and discolored) suggested that failure occurred after forging, but while the parts were still hot. These cracks were not visible during hot inspection following forging because they were masked by the forging lubricants employed. Cracks were located at the transition between the back-extrusion wall and the "slug" of each piece, and traveled in a circumferential direction. A spiral network of cracks extending the full length of the back-extrusion was also present in Serial 4. Ultrasonic inspection indicated that the crack was approximately 3/8-inch deep. The defects are shown in Figure 46 after dye-penetrant inspection.

Examination of the back-extrusion tooling following forging revealed that the punch was not adequately supported for the pressures required. A locating dowel between the punch retainer plate and the press ram spacer plate had deformed due to the extremely high forces generated from the metal's strength at relatively low temperatures. As a result, the punch was driven into the punch retainer plate approximately 1/2 inch on the deepest side. This condition caused the punch axis to be out of parallel with the billet axis under forging pressure. During extraction of the punch, the punch re-aligned itself against its retainer ring so that its axis tended to be parallel to the billet axis. This, however,

1 Hayes, A. F. and Yoblin, J. A., "Beryllium Forging Program," Contract AF33(600)-36795 with the U.S. Air Force, WPAFB-MTL Report ASD TR-62-7-647, Ladish Co., June 1962

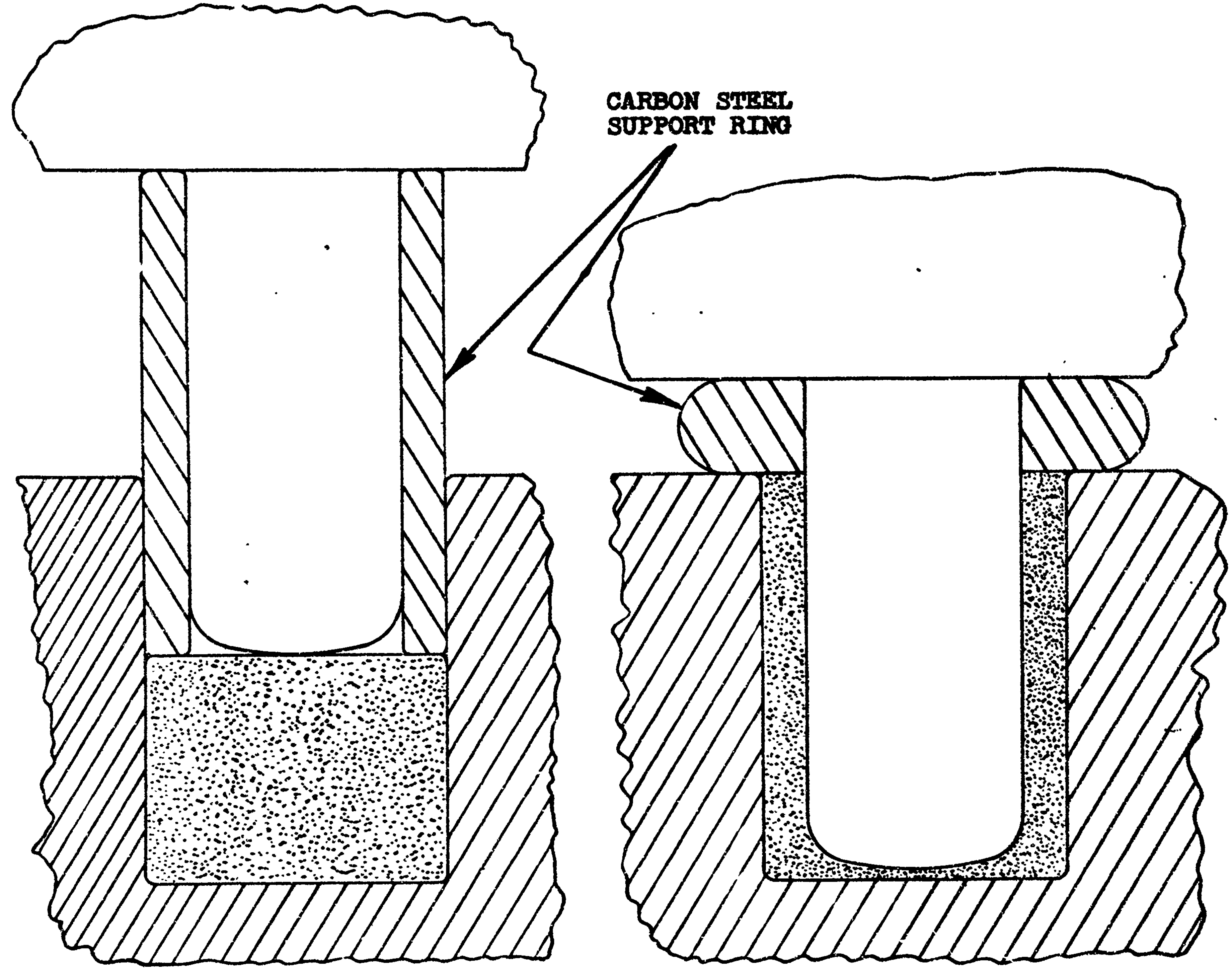


FIGURE 44

SCHEMATIC ILLUSTRATION OF HYDRODYNAMIC RESTRAINT USED FOR BACK-EXTRUDING BERYLLIUM CYLINDERS

TABLE XXIII

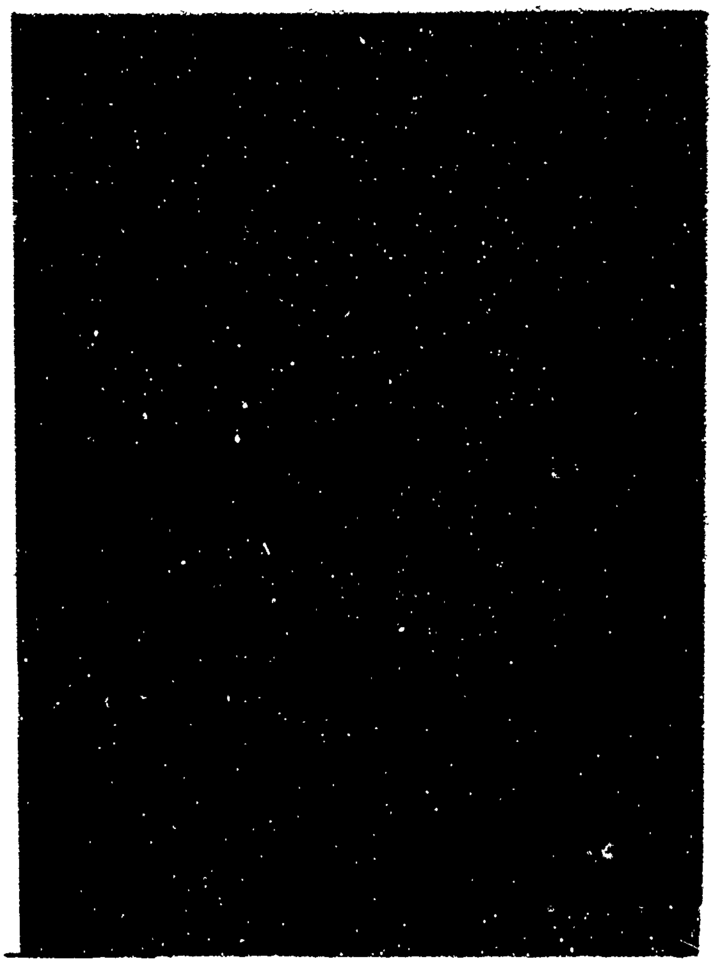
SUMMARY OF THE BACK-EXTRUSION OPERATION

FORGING PARAMETER	2.5 : 1 REDUCTION RATIO	3.4 : 1 REDUCTION RATIO
Billet Serials Involved	2, 4, 7	1, 3, 5, 6, 8, 10
Forging Temperature (°F)	1350	1350
Time Held at Temperature (Minutes)	120 to 130	30 to 110
Die Temperature (°F)	800	700
Forging Load (Tons)	1700 to 2250	2500 to 3400
Post-Forging Thermal Treatment	1325°F for one hour	1325°F for one hour
Cooling Method	Furnace-cooled at a rate not to exceed 50°F per hour to 150°F.	

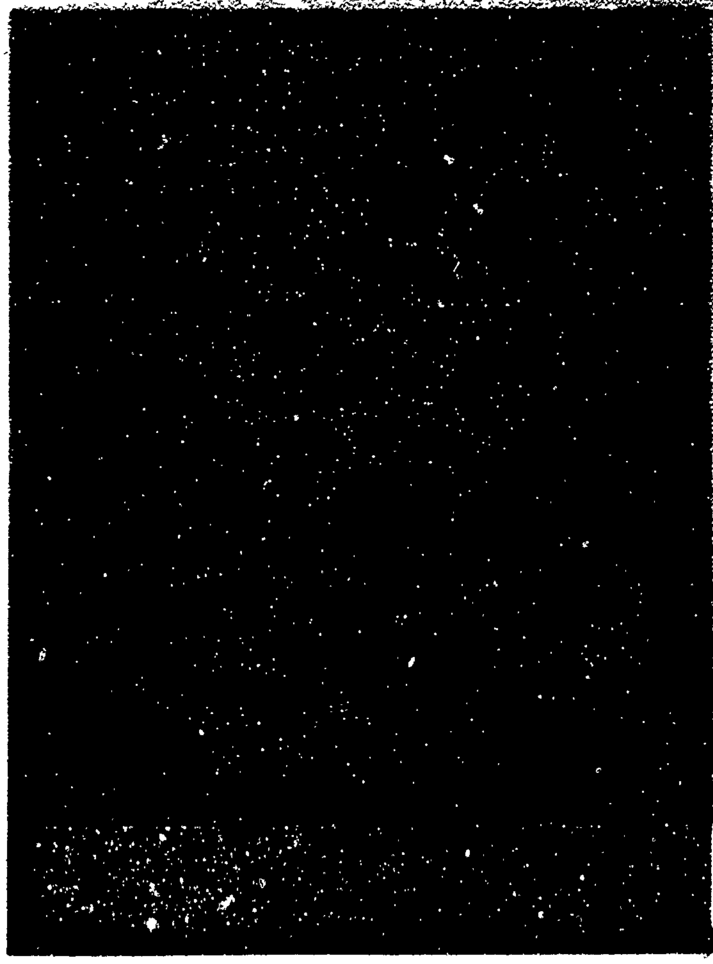
TABLE XXIV

BERYLLIUM BACK-EXTRUSION OPERATION FORGING LOAD REQUIREMENTS

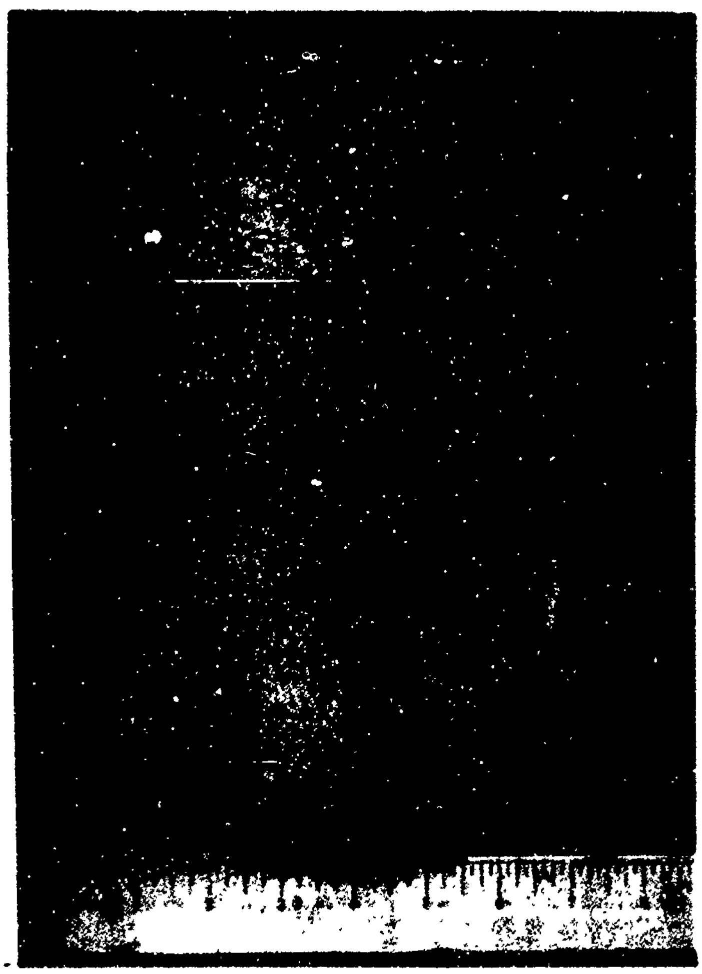
BILLET SERIAL	EXTRUSION RATIO	EXTRUSION LOAD (TONS)	LOAD AT END OF RAM STROKE (TONS)	TOTAL EXTRUSION TIME (SECONDS)
2	2.5 : 1	2046	3142	8.6
4	2.5 : 1	1717	2338	8.0
7	2.5 : 1	2265	3288	9.4
1	3.4 : 1	2740	3617	7.5
3	3.4 : 1	3398	3946	8.2
5	3.4 : 1	3032	3800	7.0
6	3.4 : 1	2521	2777	6.0
8	3.4 : 1	2813	3763	7.4
9	3.4 : 1	2886	3617	5.8
10	3.4 : 1	2959	3763	7.6



SERIAL NO. 2



SERIAL NO. 4

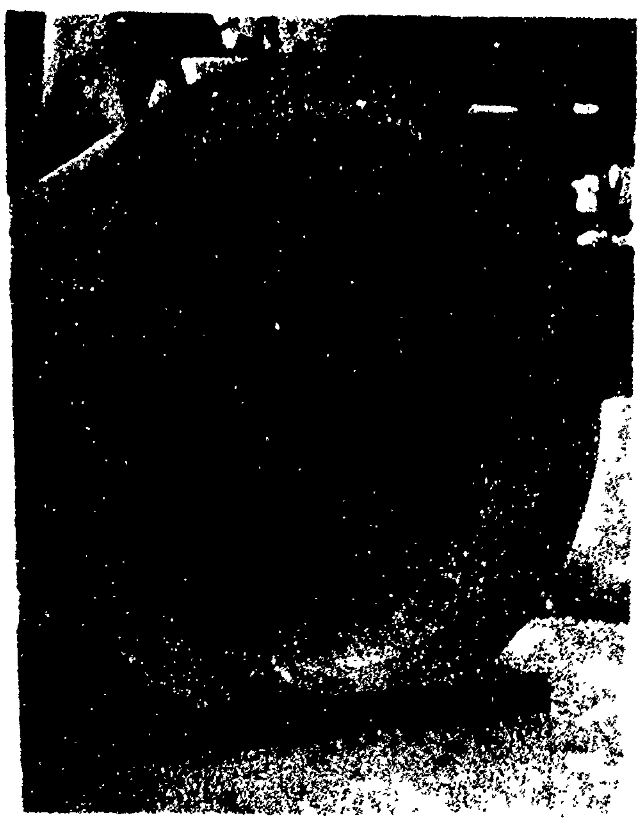


SERIAL NO. 7

FIGURE 45

SURFACE CONDITION OF OUTER DIAMETERS OF BILLETS BACK-EXTRUDED AT A RATIO OF 2.5 : 1

SERIAL NO. 2



SERIAL NO. 4

SERIAL NO. 7

FIGURE 46

CONDITION OF INNER DIAMETERS OF CYLINDERS AFTER BACK-EXTRUSION AT A RATIO OF 2.5 : 1

caused high bearing pressure along one side of the inner diameter of the extruded beryllium as the punch was withdrawn. It is believed that the upward force caused by the punch dragging along the side of the extrusion under high pressure was sufficient to initiate the cracking which occurred on the inner diameter. This tooling problem was not detected during forging because the punch extraction pressures re-aligned the punch prior to each back-extrusion. Tooling was redesigned with a more massive support under the punch to prevent recurrence of this problem.

The remaining seven billets were programed for back-extrusion to 5/8-inch wall thickness at the higher ratio of 3.4-to-one. The forging parameters and pressure requirements are listed in Tables XXIII and XXIV referenced previously. Extrusion tears were again observed on most of the extrusions, except on Serial 1. Wall-thickness variation was also observed, which showed that punch-to-pot-die alignment was not readily maintained at the higher extrusion ratio. Adjustments of up to 1/8 inch were required during the run.

Examination of the back-extrusions following cleaning revealed the following conditions, as illustrated in Figures 47 through 50:

a. Back-extrusion tears were again present on the outer diameter. The same correlation of defect severity with prior working was also evident in these back-extrusions. The upset-forged billets with prior grainflow perpendicular to the direction of the back-extrusion operation ruptured more severely than the vacuum-hot-pressed block or forward-extruded-and-upset-forged billets.

b. A crack at the transition between the slug and the back-extrusion wall developed on Serial 1. The defect traveled approximately one inch and was 0.100 inch deep.

c. Severe cracks developed through the wall on Serials 3, 5, 6, and 10. The crack in Serial 6 traveled about 1.5 inches from the top of the back-extrusion. The crack length in Serial 5 was approximately 3.5 inches. Serials 3 and 10 had cracks through the back-extrusion wall that traveled the full length of the back-extrusions.

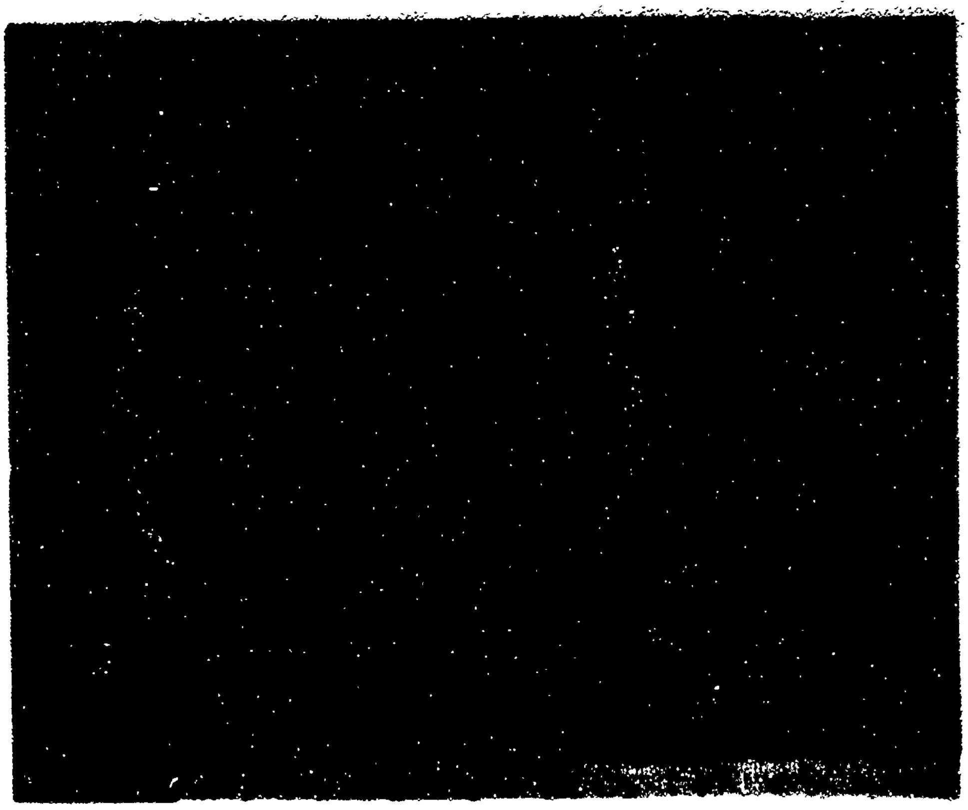
Examination of the tooling after back-extrusion at this higher ratio did not reveal any irregularities. Dimensional analysis of the forgings indicated that the most severe cracking occurred in the pieces exhibiting the greatest wall-thickness variation. The cracks through the wall were located in the area where the extrusion wall was the thinnest. A review of the forging loads revealed that Serials 3, 5, and 10 required the greatest extrusion loads. The cracks apparently initiated during stripping from the punch because of the wall-thickness variation and the increased stripping pressures on the beryllium for thinner-walled extrusions

SERIAL NO. 1

SERIAL NO. 3

FIGURE 47

CONDITION OF CYLINDERS AFTER BACK-EXTRUSION
AT A RATIO OF 3.4 : 1



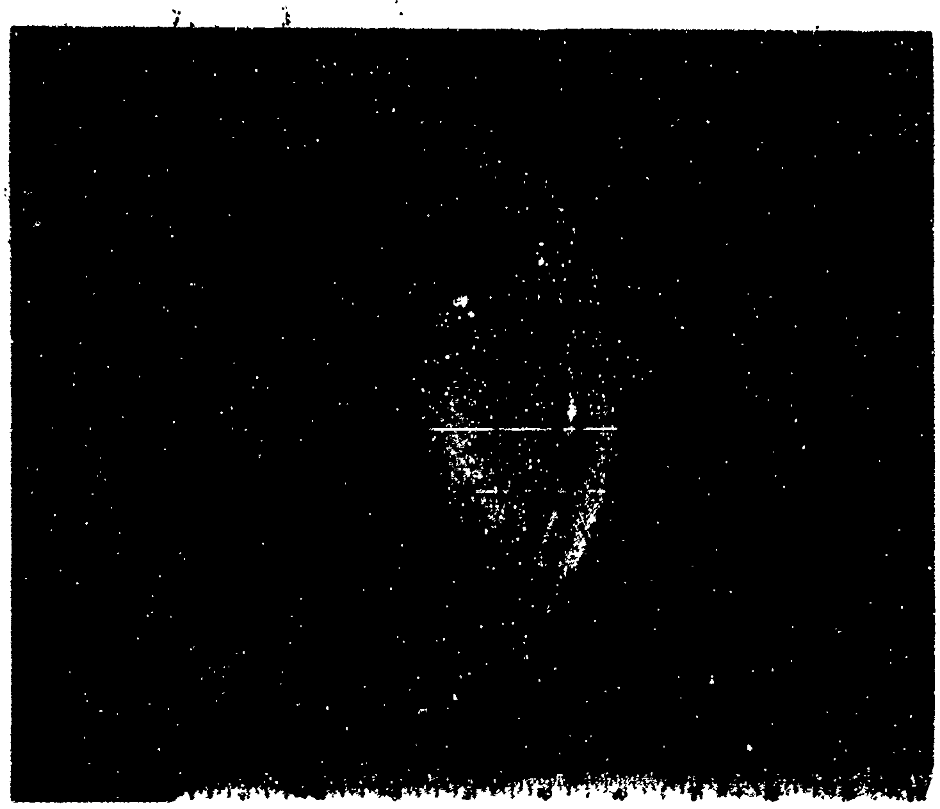
SERIAL NO. 5

SERIAL NO. 6

FIGURE 43

CONDITION OF CYLINDERS AFTER BACK-EXTRUSION
AT A RATIO OF 3.4 : 1

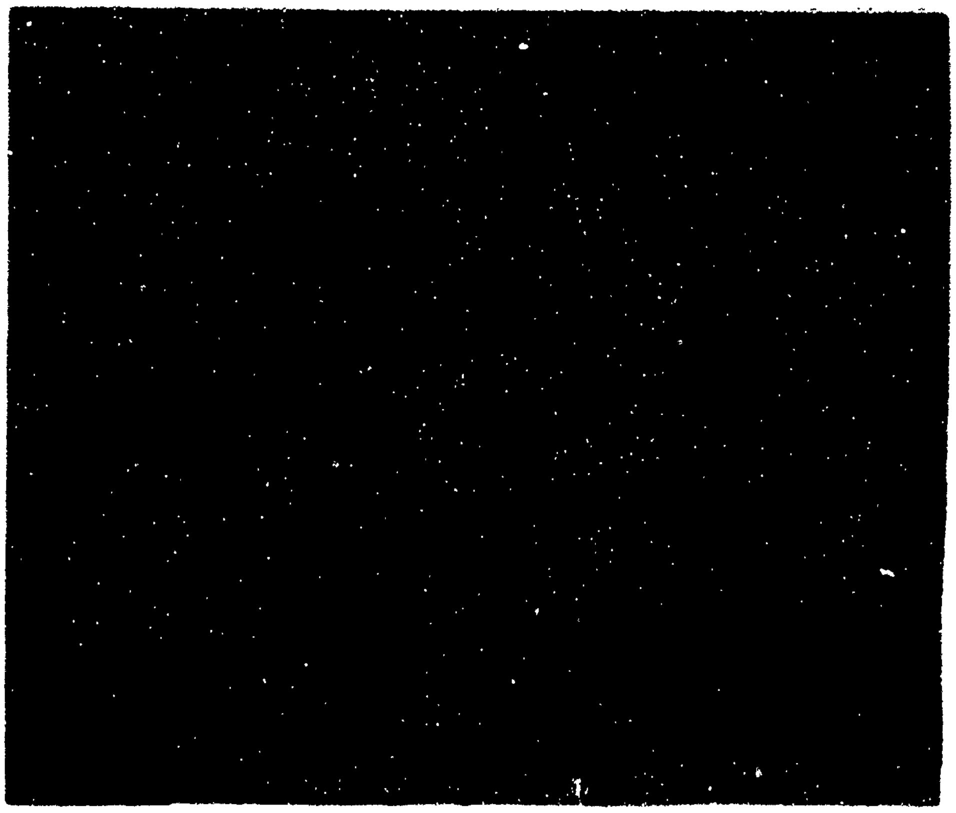
SERIAL NO. 8



SERIAL NO. 9

FIGURE 49

CONDITION OF CYLINDERS AFTER BACK-EXTRUSION
AT A RATIO OF 3.4 : 1



SERIAL NO. 10

FIGURE 50

CONDITION OF CYLINDER AFTER BACK-EXTRUSION
AT A RATIO OF 3.4 : 1

at the 3.4-to-one ratio. The wall variation created an area of weakness. The thinner wall required use of a larger punch, and therefore created greater surface area during stripping. The stripping force required was therefore higher and was applied to a smaller cross section, so that the pressure on the beryllium was significantly higher.

4. Forming Operations

A concept was established during this program for forming conical beryllium configurations from cup-shaped preforms. Model studies conducted on the two-inch-diameter beryllium cylinders showed the cone-forming concept was definitely feasible and worthy of development on a larger scale. The initial program plan called for evaluation of the forming technique using the two wall thicknesses produced during extrusion. However, all billets developed ruptures of varying severity during the back-extrusion operation as described earlier in this section. As a result, none of the pieces could be machined to the desired geometry for the cone-forming operation. Therefore, the condition of the cylinders precluded an effective evaluation of the cone-forming operation with regard to adequacy of the die design, wall thickness, restraint requirements, filler materials, and forming temperatures. The defects which developed during back-extrusion necessitated a revised course of action. The range of wall thicknesses was changed from the 1/2- to 3/4-inch planned to 5/16 to 9/16 inch. The number of sound forming blanks was reduced from ten to five, one of which had the bottom slug removed. Three of the defective cylinders were used for mechanical property evaluation. The other two were used for tooling tryouts. The extruded blanks used for the forming tryouts are described in Table XXV.

Three blanks with different forging histories (Serials 2, 4, and 6) were selected for the first tryout. Serial 6 required a carbon-steel, outer-diameter jacket to accommodate tooling fabricated for cone forming. The length of this piece was reduced to remove the defective areas. The wall thicknesses of Serials 2 and 4 were half of that programed and defects along the inner diameter remained in both pieces. The purpose of the first tryout was to evaluate tooling performance and material response for the newly-devised cone-forming operation. The forming parameters are also listed in Table XXV.

Serials 2 and 4 which had cracks remaining from back-extrusion failed catastrophically. Serial 6 developed a severe network of cracks originating at the bottom. These tryouts showed that the tooling performed well and could be used effectively for subsequent tryouts.

Serial 6, which had been free of defects prior to forming and had been formed inside a thin jacket, was sectioned into halves. One

TABLE XXV

CYLINDRICAL BERYLLIUM PREFORM DESCRIPTIONS AND FORMING PARAMETERS

SERIAL NO.	WALL THICKNESS (INCHES)	PREFORM CONDITION	JACKET USED	FILLER MATERIAL	TYPE OF RESTRAINT	FORMING TEMPERATURE (°F)	DIE TEMPERATURE (°F)
2	5/16	Cracks remained from extrusion.	1/32-inch mild steel	Molded graphite	None	1200	800
4	5/16	Cracks remained.	None	Molded graphite	None	1200	800
6	1/2	Height reduced to 6-1/4 inches.	1/8-inch mild steel	Molded graphite	None	1200	800
1	17/32	Local dressout on inner diameter.	None	Molded graphite	1-1/2-inch mild steel disc	1325	800
7	7/16	Bottom removed from cylinder; height reduced to 5-3/4 inches.	None	None	One-inch thick mild steel ring	1325	800
8	9/16	Local dressout on inner diameter.	None	Molded graphite	1-1/2-inch mild steel disc	1325	800
9	15/32	Local dressouts on outer diameter.	1/8-inch mild steel	Brass	1-1/2-inch mild steel disc	1325	800

half-section with its steel jacket intact is shown in Figure 51. As noted, the jacket pushed ahead of the beryllium during the forming operation and offered little restraint to the beryllium. The closed end of the cone blank must accommodate the internal pressure of the graphite and the bending stresses which develop during forming as the minor diameter of the conical frustum is shaped.

In view of this condition, it appeared desirable to introduce restraint at the bottom location to minimize the tensile stresses which develop. This could be accomplished by using hot steel discs placed beneath the cylinder to be formed. The shape and size of the most appropriate disc was one of the parameters which required investigation.

During the evaluation of the forming tryouts, the following variables were isolated as areas requiring investigation for this specific operation:

a. Wall-thickness-to-diameter ratio;
b. Hydrostatic restraint;
c. Filler materials;
d. Forming temperature;
e. Strain rate.

The four remaining cylindrical blanks were formed using parameters judged capable of providing maximum assurance for obtaining sound cones within the physical limitations of the input blanks. Wall thicknesses were the maximum possible. However, the walls were still thinner than planned in most instances, and all pieces had areas of local dressouts. A 1-1/2-inch-thick hot steel forward support was used to provide restraint. Both graphite and brass filler materials were used to evaluate their abilities to minimize wall thickening. The forming temperature was raised from 1200 to 1325°F. Although uniaxial tensile ductility is higher at 1200°F, results of forming evaluations[2] and forming experience[3, 4] have shown that greater success for accommodating the complex stresses of forming is attained at higher temperatures (1300 to 1350°F). A forging rate of approximately 30 inches per minute ram travel was used. The specific dimensions and conditions used for forming the four blanks are shown in previously-referenced Table XXV.

The forming operation was conducted as planned and all visible beryllium surfaces appeared free of defects prior to cleaning.

2 Williams, R. F. and Ingels, S. E., The Fabrication of Beryllium Alloys - Volume II: "Forming Techniques for Beryllium Alloys," NASA TMX-53453, July 1966

3 Oken, S. and Dilks, B. H., "Structural Evaluation of Beryllium Solar Panel Spars," AFFDL Technical Report TR-65-45, The Boeing Company, August 1966

4 Barnett, F. E., Finn, J. M., and Koch, L. C., "Beryllium Structures for Aircraft," Paper No. 660666 presented at the SAE Aeronautic & Space Engineering and Manufacturing Meeting, Los Angeles, California, October 3 through 7, 1966

FIGURE 51

CONDITION OF SERIAL NO. 6 AFTER FORMING AND SECTIONING. SHOWN WITH STEEL JACKET IN POSITION.

Visual examination following cleaning and jacket removal showed that the forming operation was generally successful. Serials 7 and 8 were free of any material defects. These two cones are depicted in Figures 52 and 53. The forward sections of Serials 8, 1, and 9 had irregular shapes due to the influence of the restraint disc. This could be corrected through redesign of the restraint and/or a separate mild forming operation. Serials 1 and 9 had cracks across the forward sections which were confined to that location. Serial 9 had a circumferential crack which sheared off the nose section of the cone. The sound section of this cone is shown in Figure 54. Serial 1, shown in Figure 55, had several radial cracks across the nose. Redesign of the nose support and use of blanks having uniform wall thicknesses should minimize this problem. Use of blanks having a thicker section at the closed end could also be studied. A thickening of approximately 1/16 inch occurred in the wall of those cones which were formed using the graphite filler. No measurable increase in thickness occurred in those using the brass filler.

The basic cone-forming technique developed in this program was used successfully for producing both open-ended and closed conical frustums. Additional effort was required to more adequately define the forming parameters and to extend the technical capability for manufacturing a wider variety of conical shapes.

E. Evaluation of Phase III Subscale Cones

1. Mechanical Property Response

Three cones and three cylinders (Serials 1, 3, 5, 6, 9, and 10) were sectioned as shown in the outline in Figure 56 and tested for room-temperature tensile properties. Two additional cones, Serials 7 and 8, were retained in the as-formed condition. The remaining two cones, Serials 2 and 4, were destroyed during the extrusion and forming operations. Only limited test material was available from Cylinder 3 and Cone 6. Where possible, sections from each forging were heat treated at 1500°F for one hour and 1750°F for one hour. Tests were performed in the as-forged and as-heat-treated conditions. Results are shown in Table XXVI. Test specimen preparation techniques and the testing procedures are described in the Appendix.

Yield and ultimate strengths exceeded 78 and 90 Ksi, respectively, in the circumferential and axial directions for the cone which received the least amount of deformation (Serial 1). Higher strengths, exceeding 83 Ksi yield strength and 100 Ksi ultimate strength, were attained for the cones which received greater amounts of deformation. Yield strength decreased significantly after the one-hour 1750°F thermal treatment, but average yield strength remained above 70 Ksi. The yield strengths attained before and after the 1500°F treatment compared well with previously developed data.[5]

5 Koslinski, E. J. and N[illegible], R. J., "Development of Beryllium Forging Techniques for [illegible] Components," Interim Engineering Report No. [illegible], [illegible] AF[illegible]-[illegible], MM Project No. [illegible], Dallas [illegible]

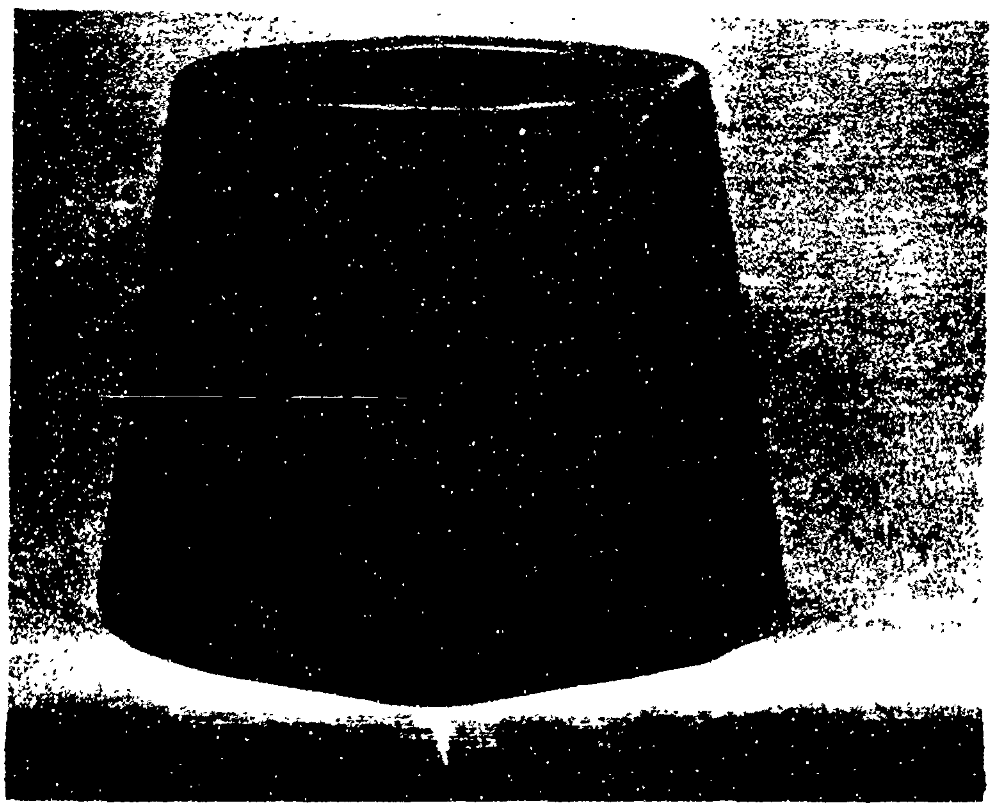


FIGURE 52

CONE NO. 7, SHOWN IN THE AS-FORMED CONDITION.

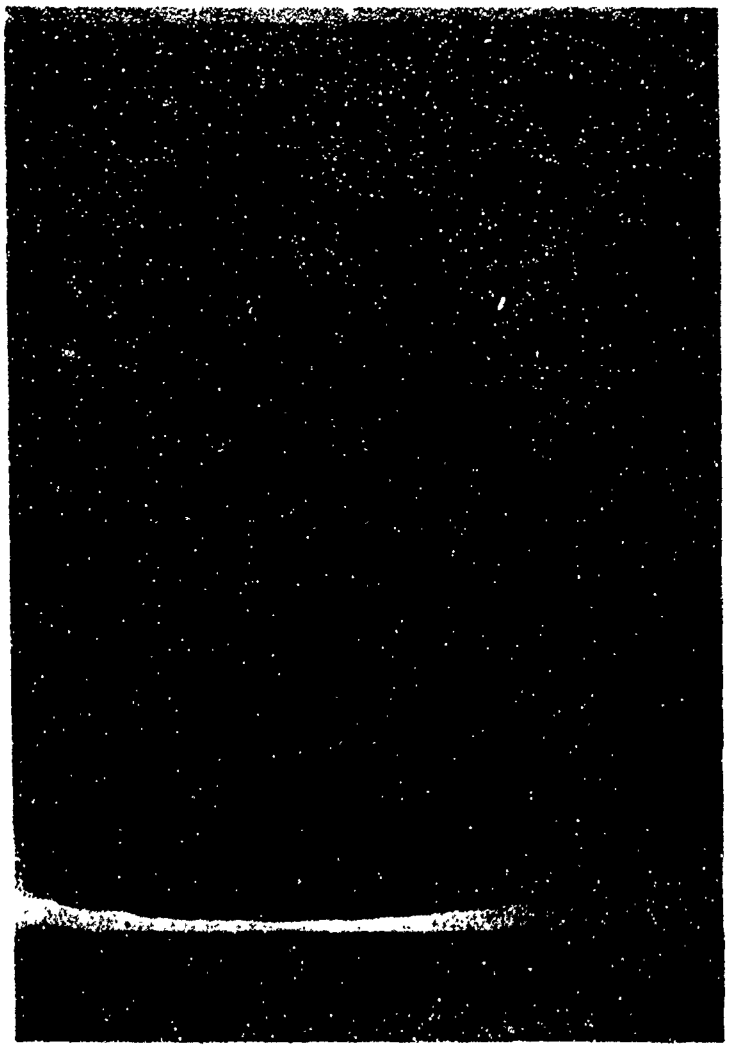


FIGURE 53

CONE NO. 8, SHOWN IN THE AS-FORMED CONDITION.

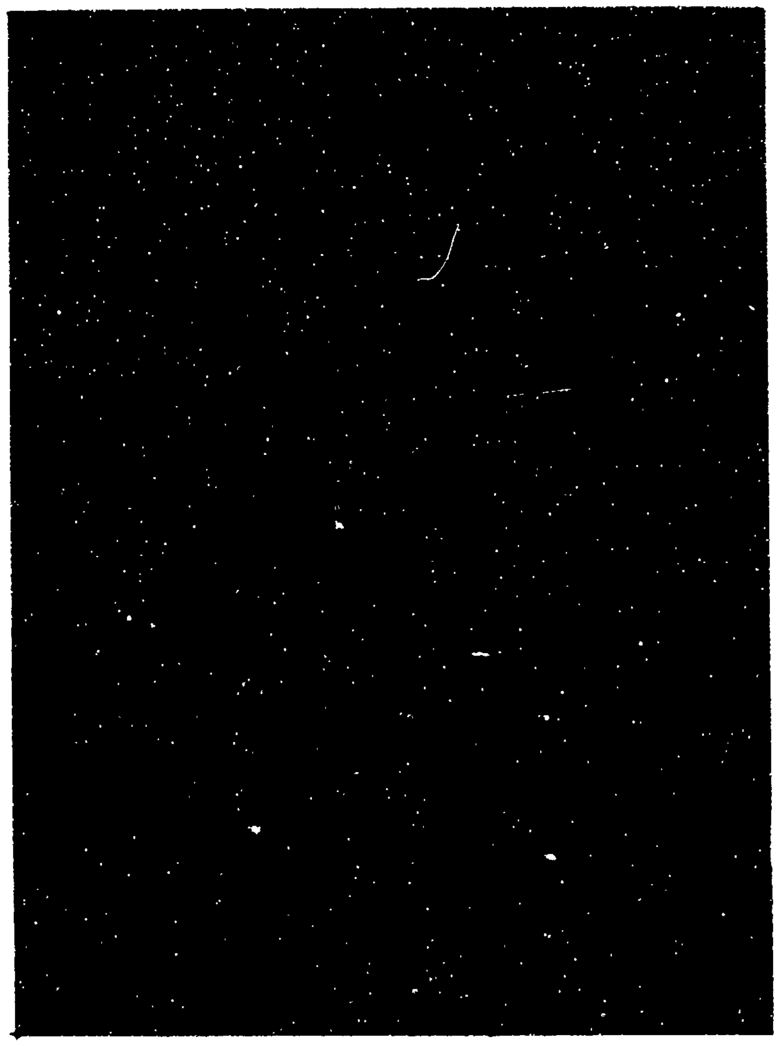


FIGURE 54

CONE NO. 9, SHOWN IN THE AS-FORMED CONDITION WITH NOSE SECTION REMOVED.

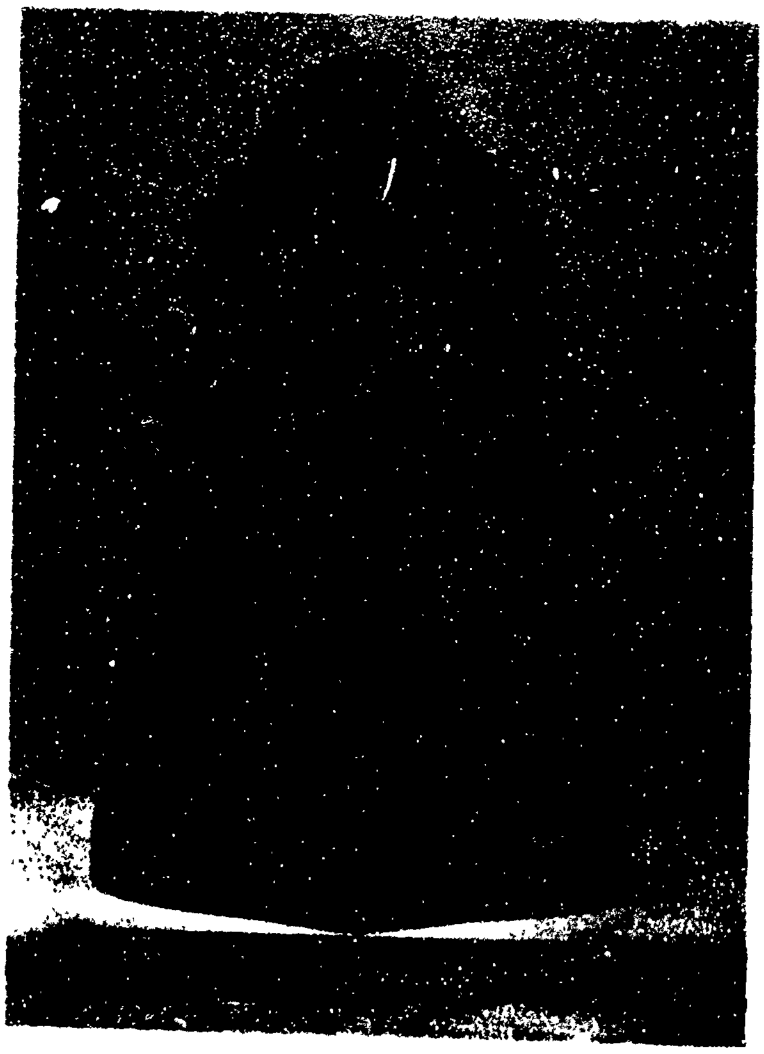


FIGURE 55

CONE NO. 1, SHOWN IN THE AS-FORMED CONDITION.

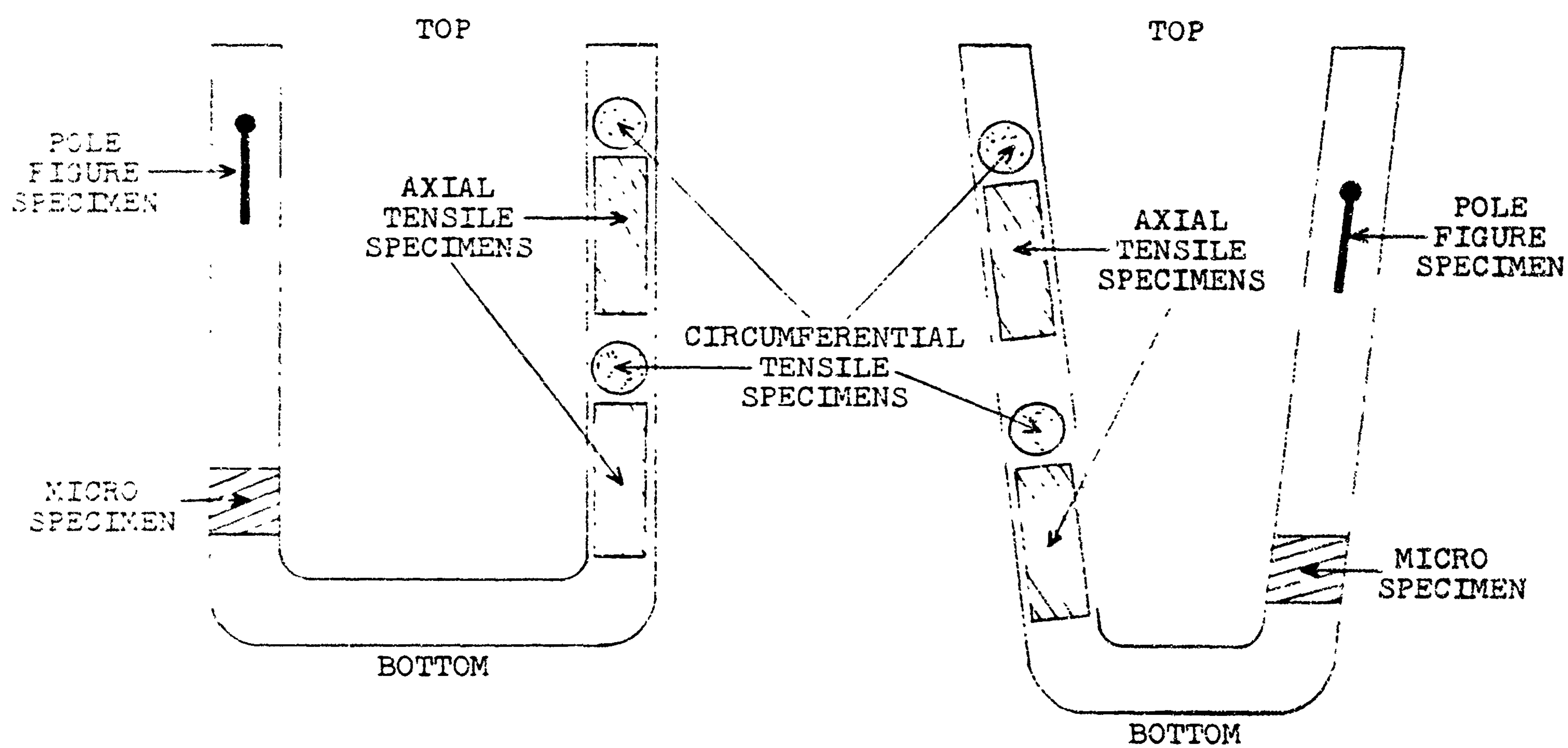


FIGURE 56

SECTIONING DIAGRAM FOR FORGED BERYLLIUM CYLINDERS AND CONES

TABLE XXVI
ROOM-TEMPERATURE TENSILE PROPERTIES OF FORGED BERYLLIUM CONES AND CYLINDERS

SERIAL NO.	FORGING SEQUENCE	THERMAL TREATMENT	TEST DIRECTION	TEST LOCATION	YIELD STRENGTH 0.2% OFFSET (KSI)	ULTIMATE STRENGTH (KSI)	ELONGATION (PER CENT)	REDUCTION IN AREA (PER CENT)
1	Back-Extruded and Formed	1325°F - One Hour	Circ.*	Top	78.8	90.4	2.2	2.4
			Axial	Top	83.6	102.0	7.9	9.4
			Circ.	Bottom	85.6	93.0	1.7	1.7
			Circ.	Bottom	85.6	94.5	2.6	1.7
			Axial	Bottom	91.2	116.9	11.4	11.0
			Axial	Bottom	89.0	114.1	12.0	14.0
		1500°F - One Hour	Circ.	Top	80.6	89.5	2.1	2.4
			Axial	Top	88.0	98.2	4.0	4.0
			Circ.	Bottom	87.0	93.0	3.0	3.0
			Circ.	Bottom	89.4	101.0	2.3	2.4
			Axial	Bottom	93.6	114.0	13.0	14.0
			Axial	Bottom	92.0	116.0	14.3	14.0
		1750°F - One Hour	Circ.	Top	72.4	87.8	2.4	2.4
			Axial	Top	71.6	94.4	6.2	8.6
			Circ.	Bottom	74.4	89.8	3.4	3.9
			Circ.	Bottom	74.0	88.8	2.4	3.9
			Axial	Bottom	77.8	109.2	13.6	13.9
			Axial	Bottom	80.2	112.2	14.2	14.6
3	Upset and Back-Extruded	1325°F - One Hour	Axial	Top	88.6	101.3	22.0	30.2
			Circ.	Top	90.2	102.0	25.0	38.0
			Circ.	Bottom	90.6	105.7	14.0	20.0
		1500°F - One Hour	Circ.	Top	85.4	101.3	11.0	28.0
			Circ.	Bottom	83.6	101.4	26.5	30.5
		1750°F - One Hour	Circ.	Top	76.0	105.4	27.9	32.9
			Circ.	Bottom	77.0	95.2	29.0	32.0
			Circ.	Bottom	76.0	95.6	11.0	31.0
5	Upset and Back-Extruded	1325°F - One Hour	Circ.	Top	81.4	99.4	8.2	15.3
			Axial	Top	82.4	103.1	11.0	13.1
			Circ.	Bottom	85.2	103.0	19.0	22.6
			Circ.	Bottom	88.2	100.2	20.0	32.0
			Axial	Bottom	80.2	98.0	10.9	11.7
			Axial	Bottom	79.6	95.9	6.9	7.8
		1500°F - One Hour	Circ.	Top	84.0	100.7	9.0	11.0
			Axial	Top	83.4	98.4	15.0	16.8
			Circ.	Bottom	88.2	112.5	20.0	20.0
			Circ.	Bottom	88.8	100.7	15.0	17.0
			Axial	Bottom	74.4	95.8	8.1	7.8
			Axial	Bottom	81.2	97.2	17.4	16.8
		1750°F - One Hour	Circ.	Top	75.9	97.5	19.8	21.4
			Axial	Top	69.5	95.6	16.4	18.3
			Circ.	Bottom	73.9	95.8	16.0	19.0
			Circ.	Bottom	72.9	95.3	20.0	25.0
			Axial	Bottom	68.0	92.4	9.2	7.8
			Axial	Bottom	68.8	92.9	8.5	9.4
6	Forward-Extruded, Upset, Back-Extruded and Formed	1325°F - One Hour	Circ.	Bottom	90.0	98.2	1.8	2.3
			Circ.	Bottom	89.6	98.4	2.2	3.2
			Axial	Bottom	94.4	117.6	19.[illegible]	21.1
			Axial	Bottom	96.0	119.8	19.6	20.4
9	Forward-Extruded, Upset, Back-Extruded and Formed	1325°F - One Hour	Circ.	Top	91.4	111.6	20.0	27.3
			Axial	Top	85.0	94.8	3.6	1.5
			Circ.	Bottom	89.4	102.5	9.6	11.6
			Circ.	Bottom	88.0	102.5	10.4	11.7
			Axial	Bottom	97.6	122.0	20.9	21.7
			Axial	Bottom	97.2	123.4	19.2	22.6
		1500°F - One Hour	Circ.	Top	75.0	109.1	15.9	16.1
			Axial	Top	71.3	94.0	2.0	6.0
			Circ.	Bottom	73.4	99.8	8.4	9.4
			Circ.	Bottom	75.2	101.0	7.8	8.7
			Axial	Bottom	84.3	124.6	16.0	17.0
			Axial	Bottom	83.0	123.4	16.0	19.0
		1750°F - One Hour	Circ.	Top	76.0	107.4	16.0	19.0
			Axial	Top	67.4	88.5	4.0	5.0
			Circ.	Bottom	72.6	95.1	9.0	10.0
			Circ.	Bottom	71.8	94.6	10.0	17.0
			Axial	Bottom	83.6	115.4	20.0	27.0
			Axial	Bottom	83.4	119.8	14.4	15.3
10	Forward-Extruded, Upset and Back-Extruded	1325°F - One Hour	Circ.	Top	84.2	101.6	5.0	11.0
			Axial	Top	83.3	100.6	16.0	18.0
			Circ.	Bottom	90.2	101.7	25.7	26.7
			Circ.	Bottom	89.2	102.8	18.0	20.0
			Axial	Bottom	89.2	102.8	18.6	19.7
			Axial	Bottom	88.0	103.1	18.0	19.1
		1500°F - One Hour	Circ.	Top	88.1	115.0	**	**
			Axial	Top	88.8	101.8	22.4	26.1
			Circ.	Bottom	91.3	102.3	17.1	16.8
			Axial	Bottom	87.6	105.0	22.8	23.5
			Axial	Bottom	88.6	102.4	**	**
		1750°F - One Hour	Circ.	Top	67.8	87.3	4.0	6.0
			Axial	Top	68.8	92.0	8.6	8.6
			Circ.	Bottom	73.8	95.9	24.0	28.0
			Circ.	Bottom	76.9	95.8	20.0	25.0
			Axial	Bottom	76.9	98.3	21.0	26.0
			Axial	Bottom	76.5	97.2	19.2	20.4

* Circumferential.

** Test specimen fractured into three pieces; ductility measurements were not possible.

The back-extrusion operation imparted the highest yield strength in the axial direction, which was the direction of metal flow. Upset-forging imparted high yield strength in the circumferential direction. The influence of upset-forging is evident when comparing properties of Forging 1 with Forging 5. Circumferential yield strength is highest for Forging 5, whereas the reverse is true of Forging 1.

Elongation varied considerably depending upon the testing direction, forging sequence, and location. Cones produced by back-extruding and forming had limited tensile elongation (two to three per cent) in the circumferential direction and good elongation (eight to 12 per cent) in the axial direction. Cones produced by the upset/back-extrude/form procedure had good overall elongation in the axial and circumferential directions. The limited data available from Serial 3, which was upset 80 per cent and back-extruded at a 3.4-to-one ratio, showed elongation ranging from 14 to 25 per cent for the as-forged condition. The more complex forging sequences involving forward-extrusion, upset-forging, and back-extrusion operations showed consistently high elongation in the range of ten to 25 per cent at the bottom location for the two directions measured. Elongation values at the top location were not as balanced between the two directions, nor consistent with values at the bottom location.

It is, in fact, interesting to note that elongation values between the circumferential and axial directions at the top locations of Serials 9 and 10 were the reverse of what would be anticipated. Serial 10 was given the greater amount of upset-forging and should, therefore, have had higher elongation in the circumferential direction than Serial 9. However, Serial 10 had five per cent elongation, versus 20 per cent for Serial 9. Serial 10 was upset-forged in the final pass between flat dies, without the use of outer-diameter restraint. Serial 9 was upset-forged in closed dies. The difference in grainflow at the top corners of the billets may have had a significant effect upon the ductility values at this location.

No significant trend in tensile elongation results occurred between the as-forged and the as-thermally-treated conditions for any of the forged cones.

The general trends of mechanical property response as a function of the three basic forging sequences are shown in the bar charts in Figures 57 through 59. Values shown are averages at both test locations of individual cones from each basic sequence. Serial 1 was used for the back-extrude/form sequence; Serial 5 was used for the upset-forge/back-extrude/form sequence; and Serial 10 was used for the forward-extrude/upset-forge/back-extrude sequence. The balance of properties for the more complex forging sequence is very apparent in these charts. Maximum basal plane orientation, described in more detail in the following section, is included in

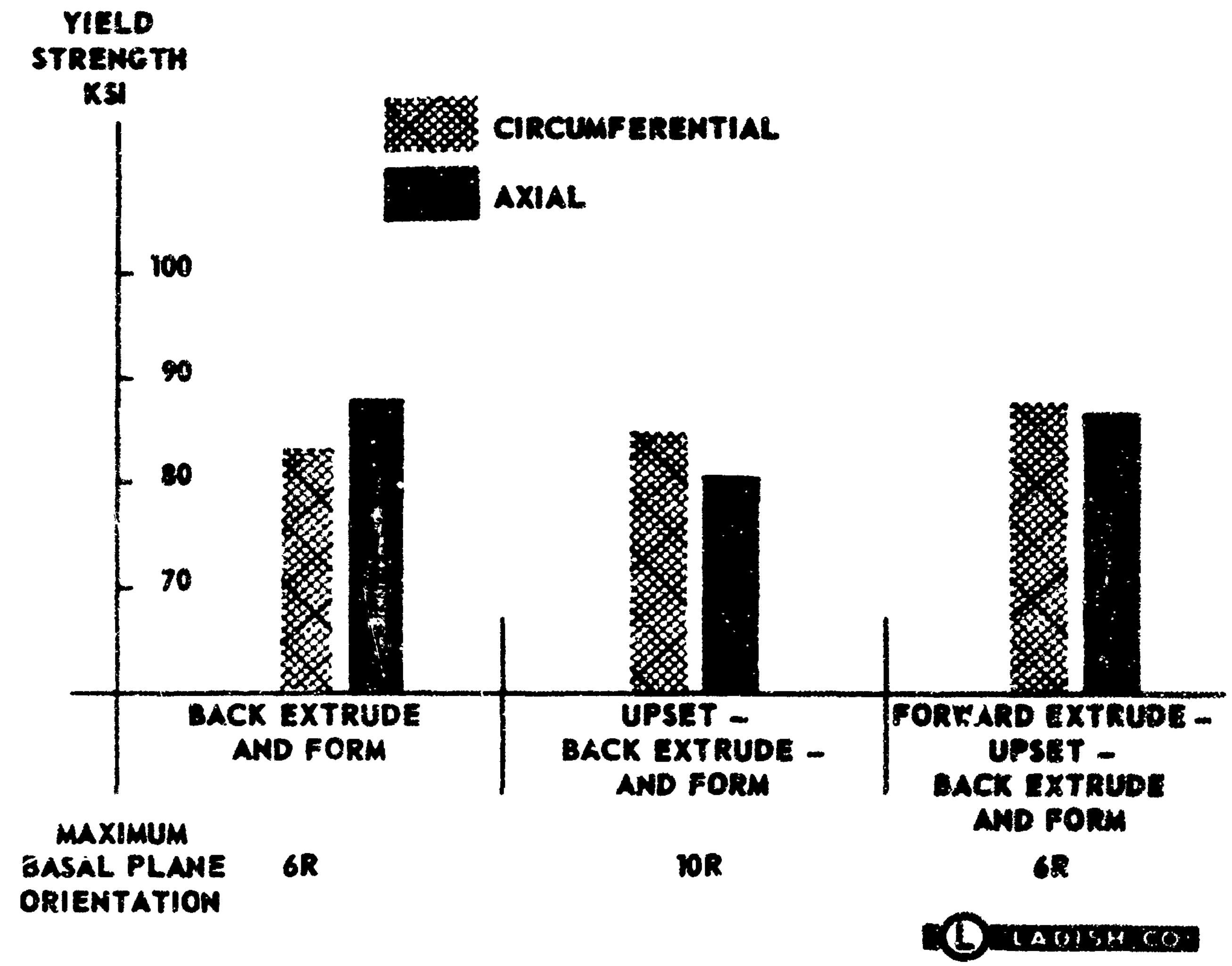


FIGURE 57

EFFECT OF FORGING SEQUENCE UPON YIELD STRENGTH OF BERYLLIUM

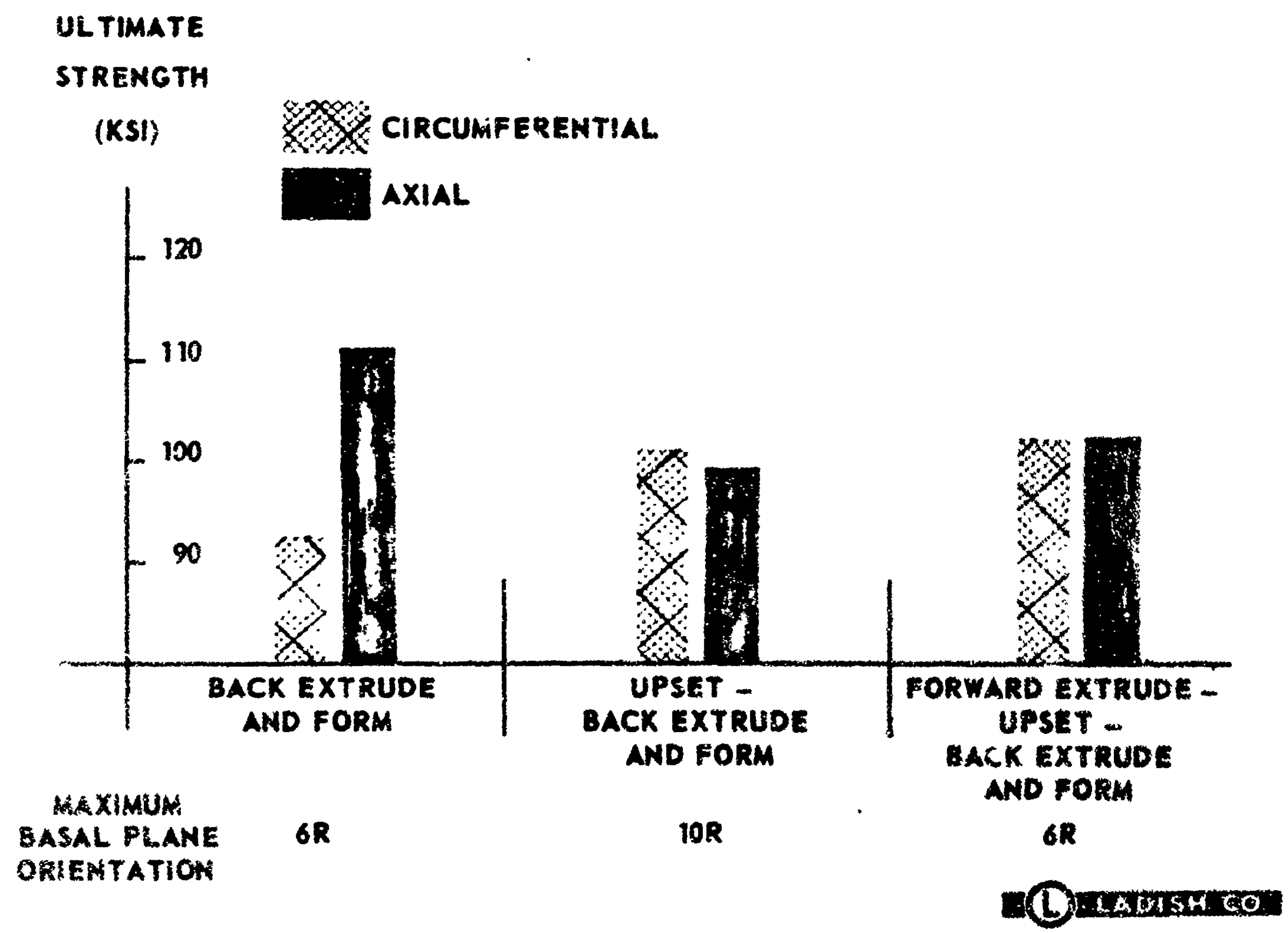


FIGURE 58

EFFECT OF FORGING SEQUENCE UPON ULTIMATE STRENGTH OF BERYLLIUM

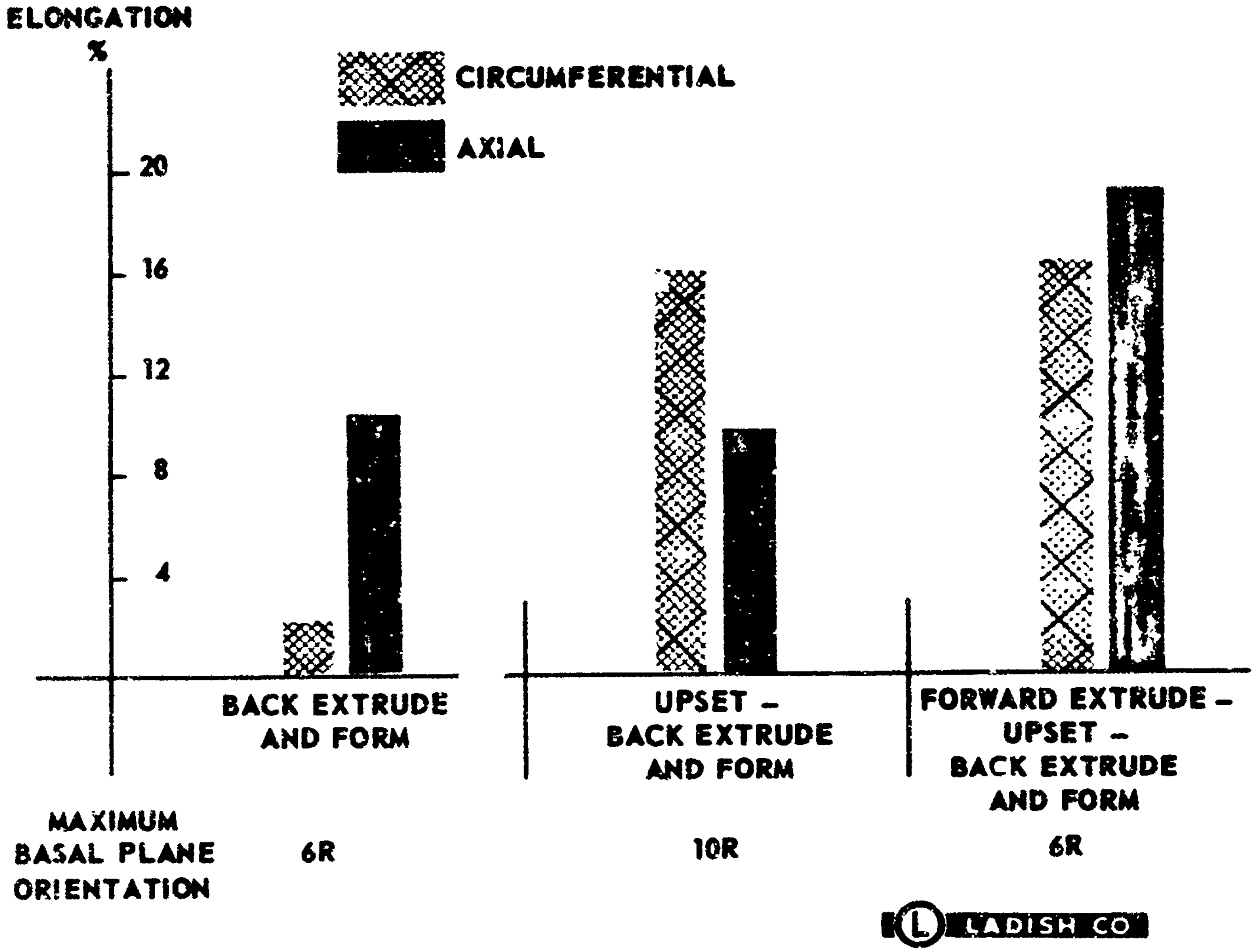


FIGURE 59

EFFECT OF FORGING SEQUENCE UPON ELONGATION OF BERYLLIUM these charts. It is interesting to note that both the simplest and the most complex forging sequences produced the same maximum basal plane orientation, which was six times the random level of isotropic beryllium.

2. Structural Evaluation

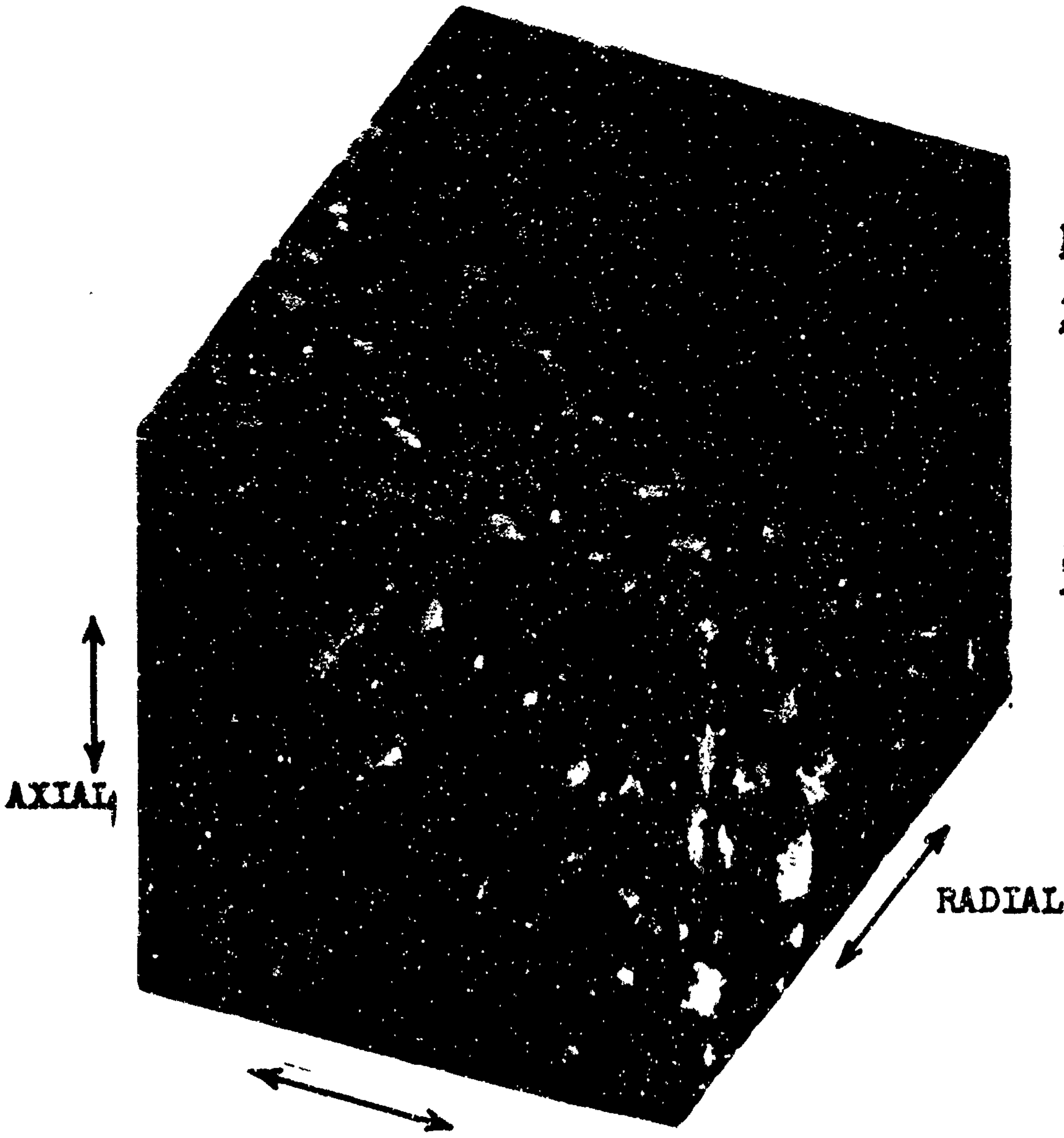
Metallographic analyses were conducted on cone or extrusion forgings representative of the three major categories of forging sequences: back-extruded and formed only (Serial 1); upset-forged and back-extruded only (Serial 5); and forward-extruded, upset-forged, and back-extruded (Serial 10). Photomicrographs of the three structures are shown in Figures 60 through 64. Figures 60 through 62 show the effects of different forging sequences. Figures 63 and 64 show the effects of thermal treatment upon Cylinder 10.

In all instances the structure was finer than that of the starting vacuum-hot-pressed block, particularly for those forgings given the greater amounts of reduction, such as Forgings 5 and 10. The average grain size of the vacuum-hot-pressed billet was approximately eight to ten microns; after forging the average grain size was approximately three to five microns. All structures appeared to be fully recrystallized. The lack of contrast between grains when viewing the axial-circumferential plane in Forging 5 indicated the presence of a high degree of preferred orientation. Significant directionality was observed in the axial-radial and axial-circumferential planes of Forging 5. The directionality observed in Serials 10 and 1 is less pronounced.

The thermal treatments of 1500°F for one hour and 1750°F for one hour coarsened the structure significantly. The 1500°F thermal treatment had the greatest effect toward increasing the grain size. Beyond 1500°F to 1750°F there was no perceptible change in the grain size. The reverse of this occurrence might be expected when considering the accompanying tensile properties, which show that yield strength is retained up to 1500°F and decreases significantly beyond that temperature. However, yield strength is not a function of grain size alone -- it is also significantly dependent upon the temperature and direction of forging.

Pole figure analyses were conducted on Forgings 1, 3, 5, 6, 9, and 10. These are shown in Figures 65 through 70. The highest degrees of preferred orientation were developed in Forgings 3 and 5 as anticipated from the metallographic analysis (upset-forged and back-extruded). Peak intensities of basal plane orientation of ten times random (10R) developed in both forgings, although the total amount of deformation was less than that given Forgings 9 and 10 (forward-extruded, upset-forged, and back-extruded). Previous work[6] showed that a [illegible]-per-cent-upset-forge operation developed a preferred orientation of approximately 7.5R. A preferred orientation of approximately 10R would be expected in a

6 Kosinski and Noel



MAGNIFICATION: 500X

FORGING HISTORY:

Back-Extruded at a 3.4:1 Ratio at 1350°F. Formed at 1325°F.

POST-FORGING THERMAL TREATMENT:

One hour at 1325°F.

ROOM-TEMPERATURE TENSILE PROPERTIES:

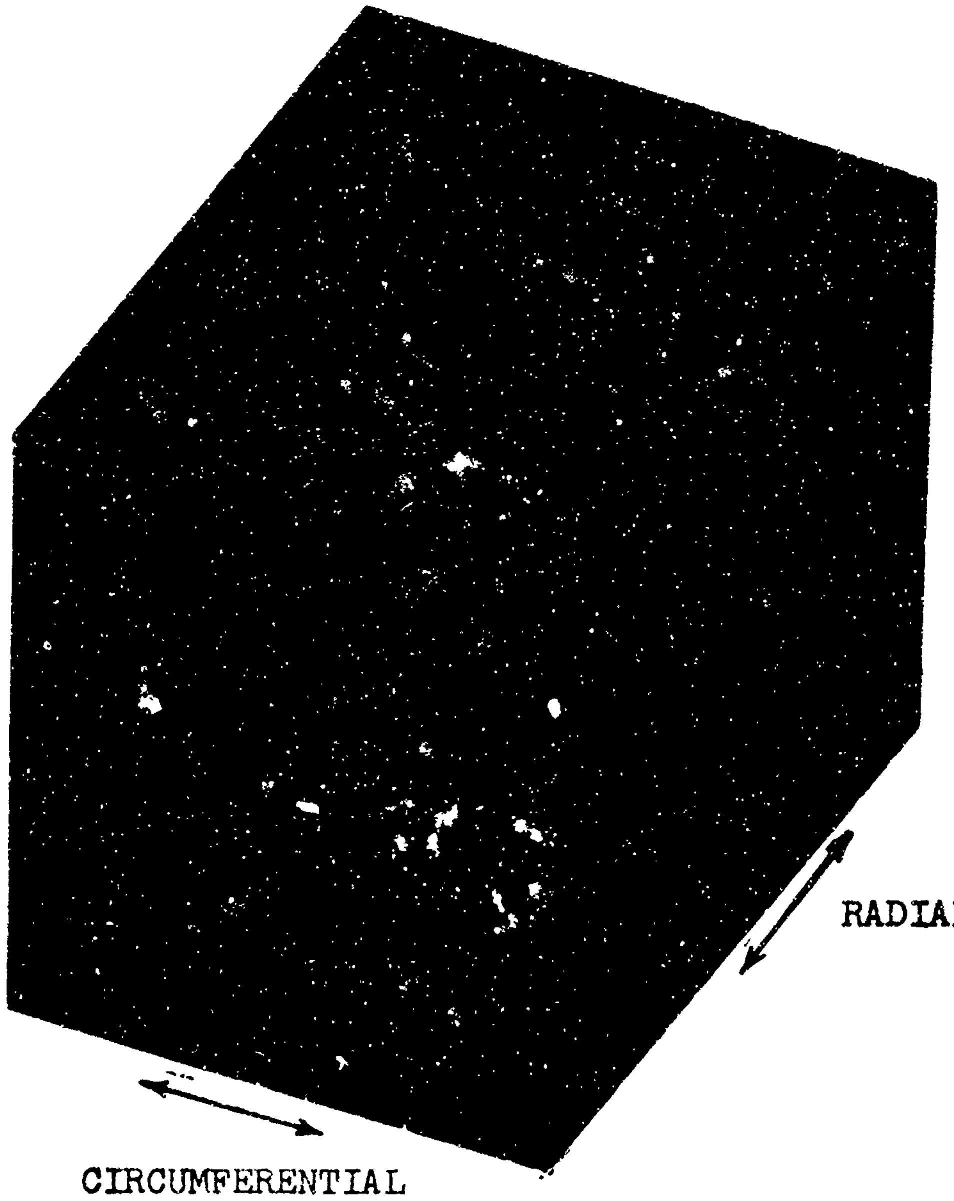
Test Direction	Test Location	0.2% Yield Strength (Ksi)	Ultimate Strength (Ksi)	Elongation (%)	Reduction in Area (%)
Circ.	Top	78.8	90.4	2.2	2.4
Axial	Top	83.6	102.0	7.9	9.4
Circ.	Bottom	85.6	93.8	2.2	1.7
Axial	Bottom	90.1	115.5	11.7	12.5

BASAL PLANE ORIENTATION:

Axial-Circ. Plane	Radial-Circ. Plane	Axial-Radial Plane	Maximum Orientation: Times Random	α	β
2 - 2.5R	0.2 - 0.5R	0.5 - 1.0R	4	18°	+10/-22°

FIGURE 60

MICROSTRUCTURE, TENSILE PROPERTIES, AND PREFERRED ORIENTATION OF CONE NO. 1



MAGNIFICATION: 500X

FORGING HISTORY:

Upset-forged 75 per cent at 1375-1350°F. Back-extruded at a 3.4:1 ratio at 1350°F.

POST-FORGING THERMAL TREATMENT:

One hoor at 1325°F.

ROOM-TEMPERATURE TENSILE PROPERTIES:

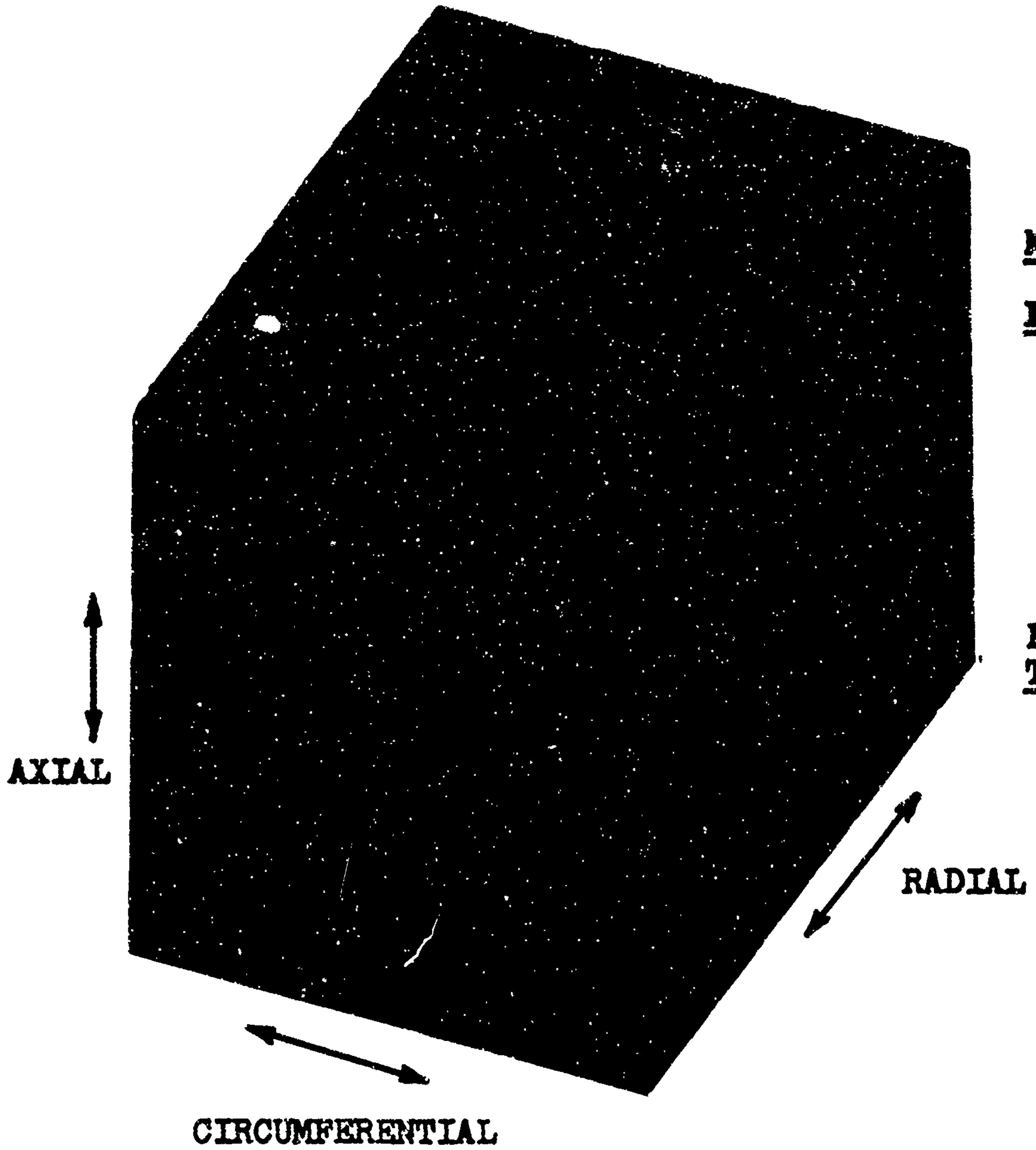
Test Direction	Test Location	0.2% Yield Strength (Ksi)	Ultimate Strength (Ksi)	Elongation (%)	Reduction in Area (%)
Circ.	Top	81.4	99.4	8.2	15.3
Axial	Top	82.4	103.1	11.0	13.1
Circ.	Bottom	86.7	101.6	19.5	27.3
Axial	Bottom	79.9	97.0	8.9	9.8

BASAL PLANE ORIENTATION:

Axial-Circ. Plane	Radial-Circ. Plane	Axial-Radial Plane	Maximum Orientation: Times Random	α	β
3 - 3.5R	0.2 0.5R	0.2 - 0.5R	10	18°	-24°

FIGURE 61

MICROSTRUCTURE, TENSILE PROPERTIES, AND PREFERRED ORIENTATION OF CYLINDER NO. 5



MAGNIFICATION: 500X

FORGING HISTORY:

Forward-extruded at a 3:1 ratio at 1400°F. Upset-forged 75 per cent at 1375-1350°F. Back-extruded at a 3.4:1 ratio at 1350°F.

POST-FORGING THERMAL TREATMENT:

One hour at 1325°F.

ROOM-TEMPERATURE TENSILE PROPERTIES:

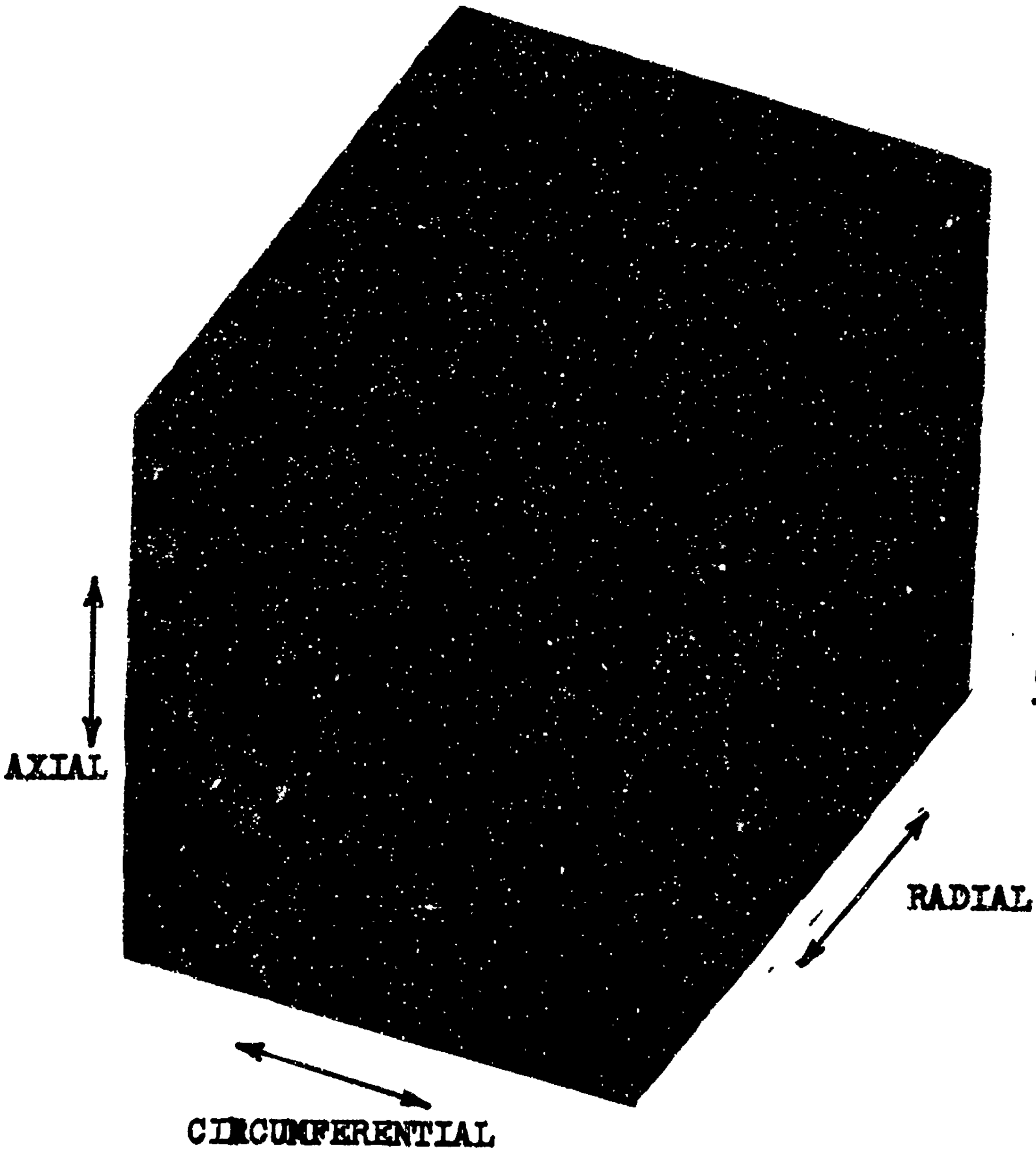
Test Direction	Test Location	0.2% Yield Strength (Ksi)	Ultimate Strength (Ksi)	Elongation (%)	Reduction in Area (%)
Circ.	Top	84.2	101.6	5.0	11.0
Axial	Top	83.3	100.6	16.0	18.0
Circ.	Bottom	89.7	102.3	21.8	23.4
Axial	Bottom	88.6	103.0	18.3	19.4

BASAL PLANE ORIENTATION:

Axial-Circ. Plane	Radial-Circ. Plane	Axial-Radial Plane	Maximum Orientation: Times Random	α	β
3.5R	0.2 - 0.5R	0.5 - 1.0R	5.5	18°	-14/-19°

FIGURE 62

MICROSTRUCTURE, TENSILE PROPERTIES, AND PREFERRED ORIENTATION OF CYLINDER NO. 10



MAGNIFICATION: 500X

FORGING HISTORY:

Forward-extruded at a 3:1 ratio at 1400°F. Upset-forged 75 per cent at 1375-1350°F. Back-extruded at a 3.4:1 ratio at 1350°F.

POST-FORGING THERMAL TREATMENT:

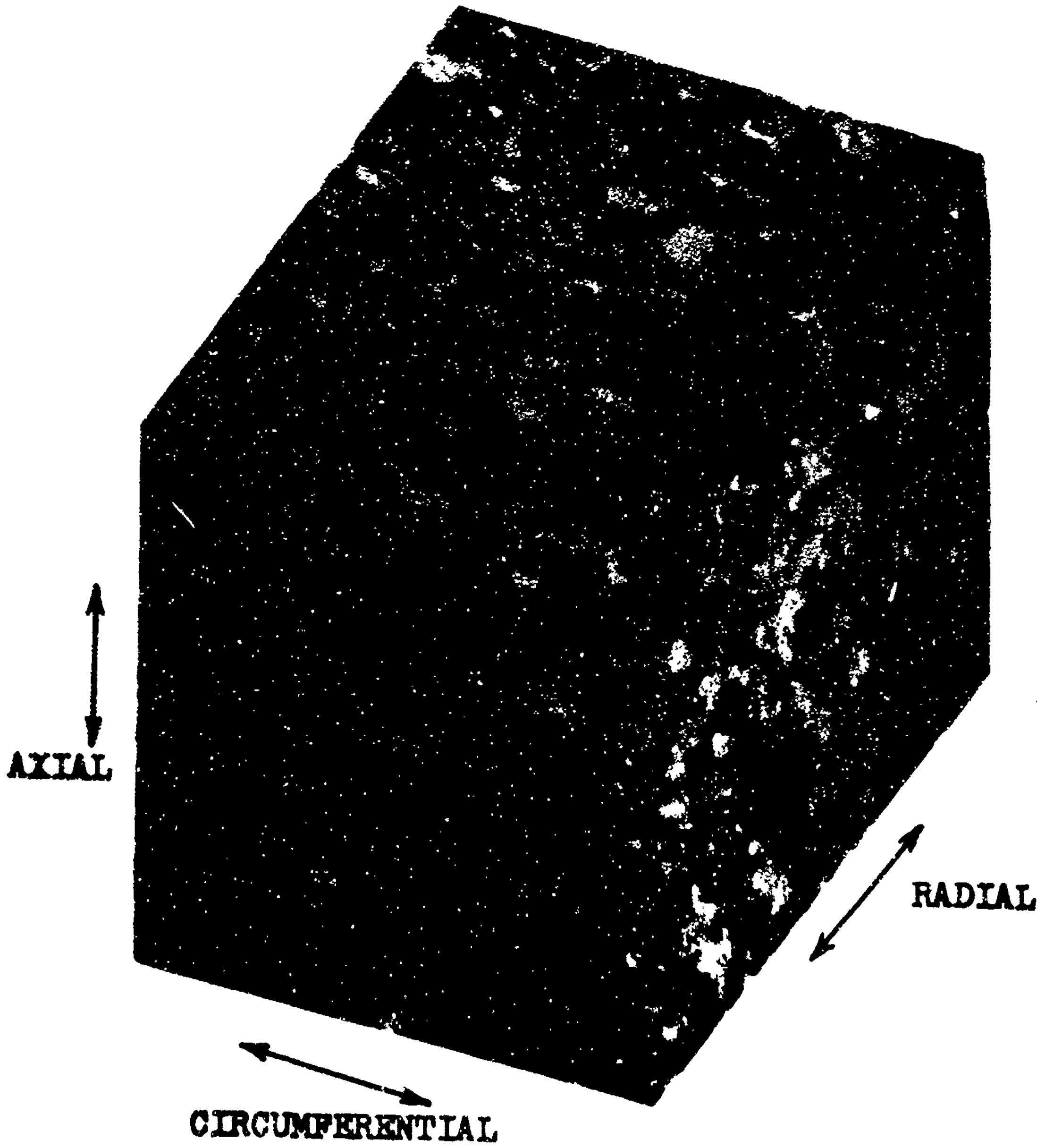
One hour at 1325°F and one hour at 1750°F.

ROOM-TEMPERATURE TENSILE PROPERTIES:

Test Direction	Test Location	0.2% Yield Strength (Ksi)	Ultimate Strength (Ksi)	Elongation (%)	Reduction in Area (%)
Circ.	Top	88.1	115.0	--	--
Axial	Top	88.8	101.8	22.4	26.1
Circ.	Bottom	91.3	102.3	17.1	16.8
Axial	Bottom	88.1	103.7	22.8	23.5

FIGURE 63

MICROSTRUCTURE AND TENSILE PROPERTIES OF CYLINDER NO. 10
AFTER ONE-HOUR 1500°F THERMAL TREATMENT



MAGNIFICATION: 500X

FORGING HISTORY:

Forward-extruded at a 3:1 ratio at 1400°F. Upset-forged 75 per cent at 1375-1350°F. Back-extruded at a 3.4:1 ratio at 1350°F.

POST-FORGING THERMAL TREATMENT:

One hour at 1325°F and one hour at 1500°F.

ROOM-TEMPERATURE TENSILE PROPERTIES:

Test Direction	Test Location	0.2% Yield Strength (Ksi)	Ultimate Strength (Ksi)	Elongation (%)	Reduction in Area (%)
Circ.	Top	67.8	87.3	4.0	6.0
Axial	Top	68.8	92.0	8.6	8.6
Circ.	Bottom	75.2	95.8	22.0	26.5
Axial	Bottom	76.7	97.8	20.1	27.8

FIGURE 64

MICROSTRUCTURE AND TENSILE PROPERTIES OF CYLINDER NO. 10
AFTER ONE-HOUR 1750°F THERMAL TREATMENT

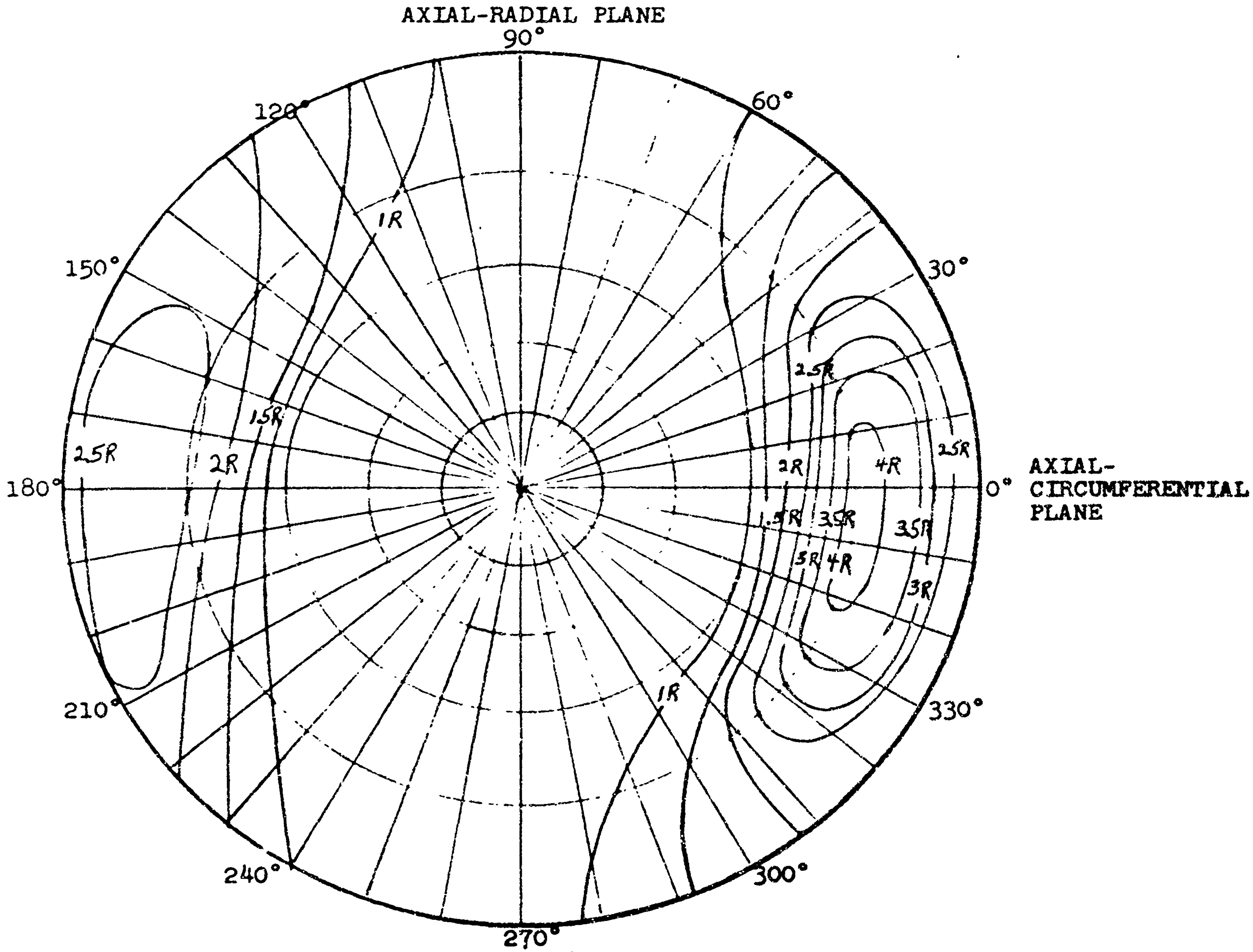


FIGURE 65

POLE FIGURE OF BASAL PLANE ORIENTATION FOR FORGING NO. 1

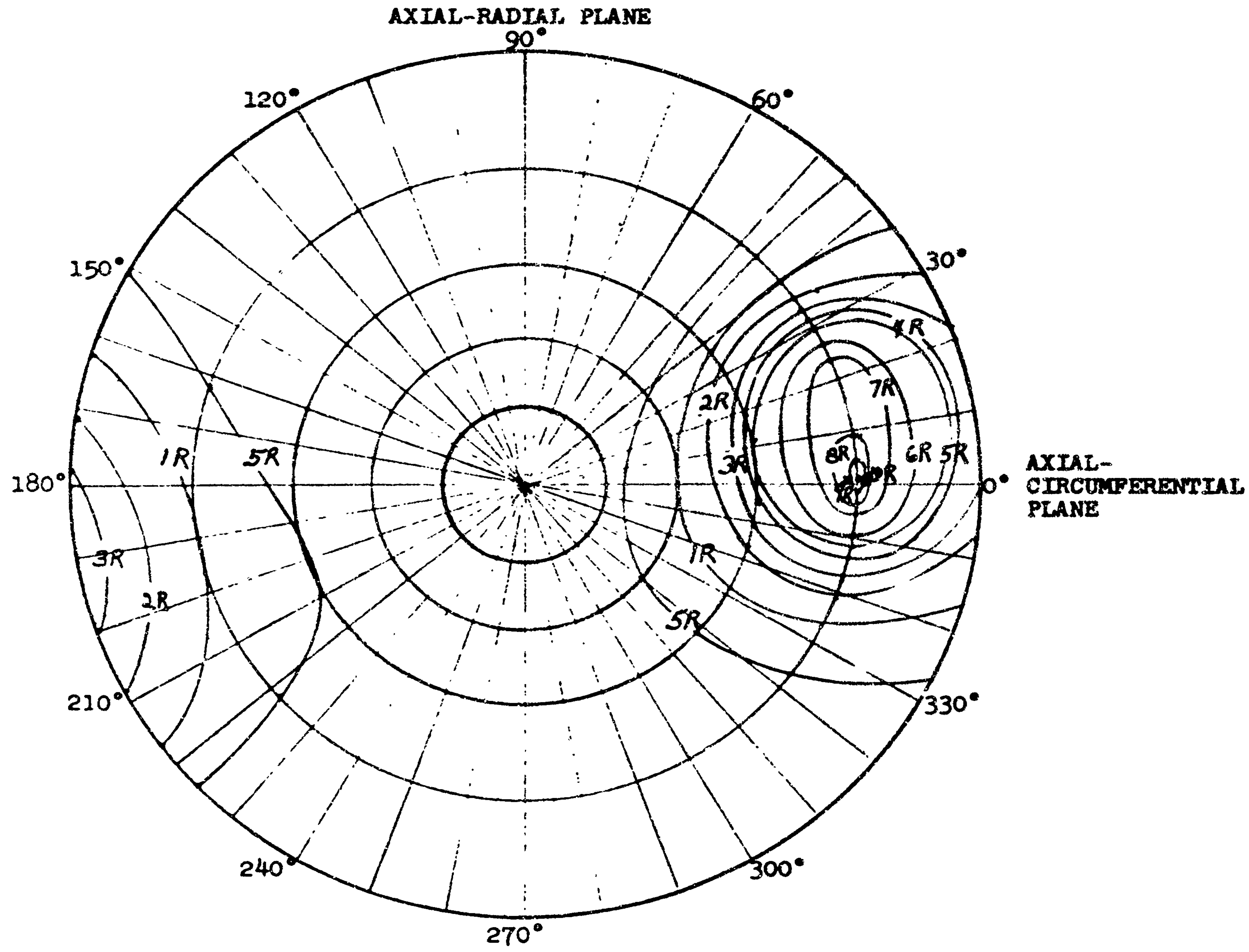


FIGURE 66

POLE FIGURE OF BASAL PLANE ORIENTATION FOR FORGING NO. 3

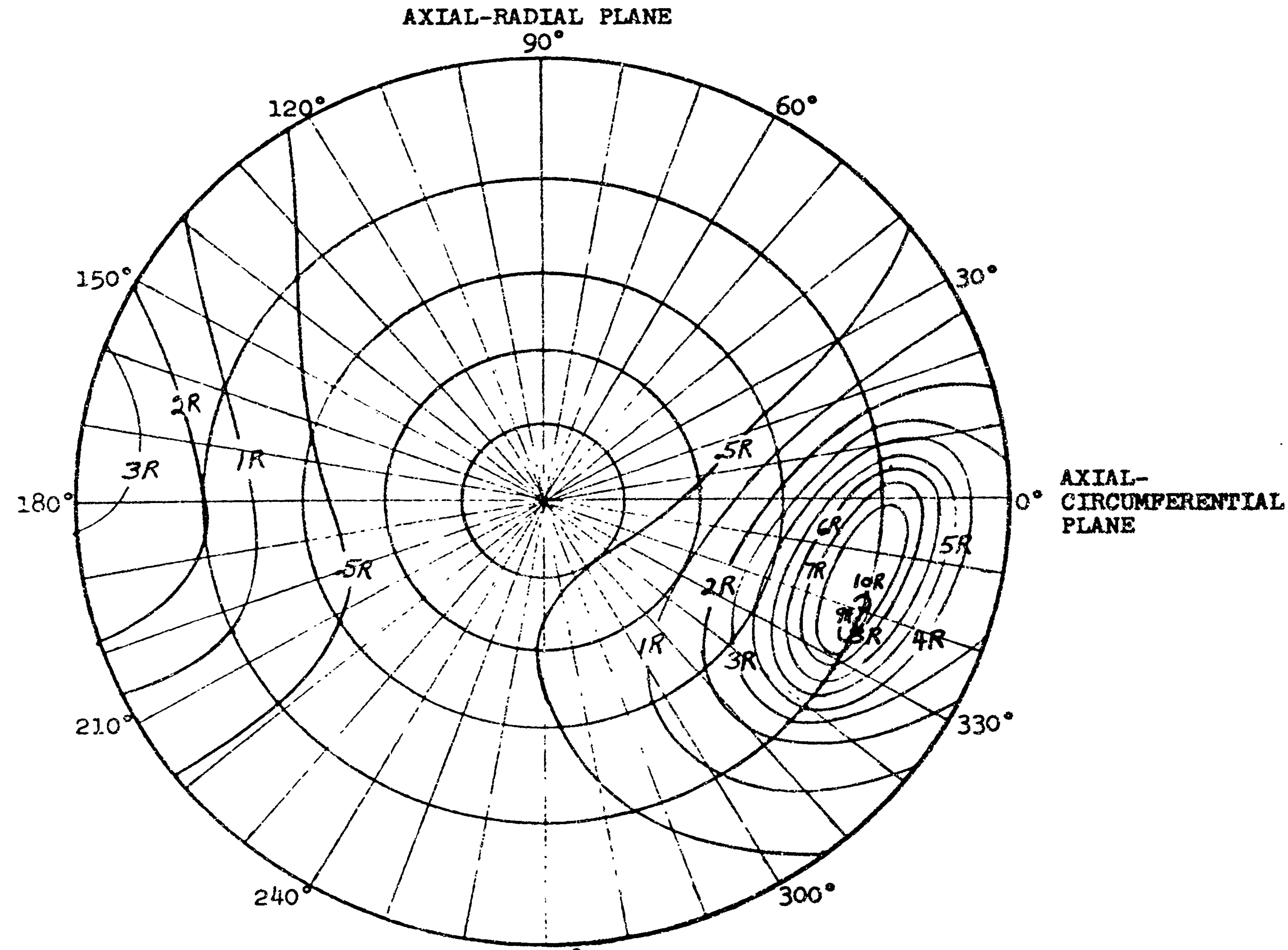


FIGURE 67

POLE FIGURE OF BASAL PLANE ORIENTATION FOR FORGING NO. 5

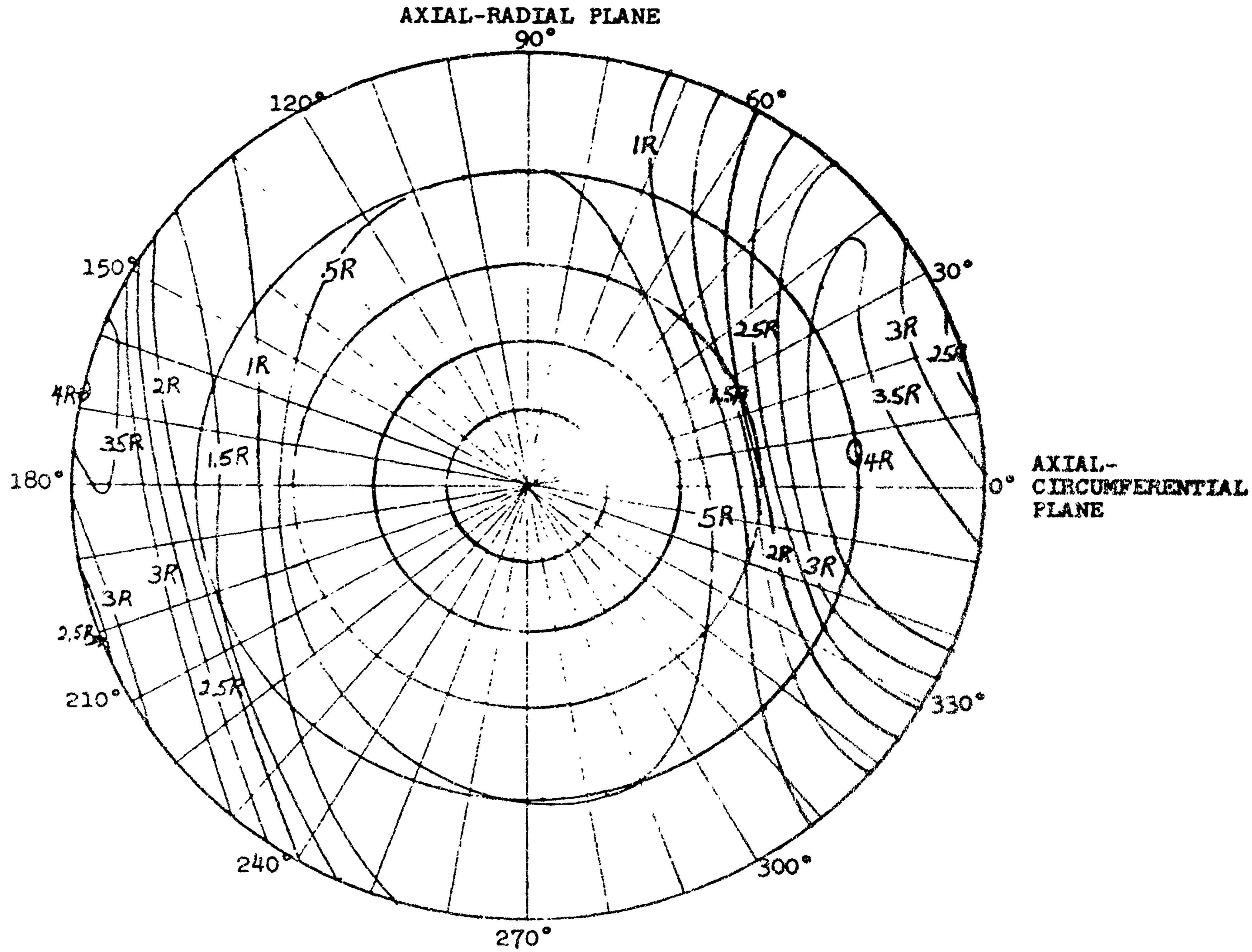


FIGURE 68

POLE FIGURE OF BASAL PLANE ORIENTATION FOR FORGING NO. 6

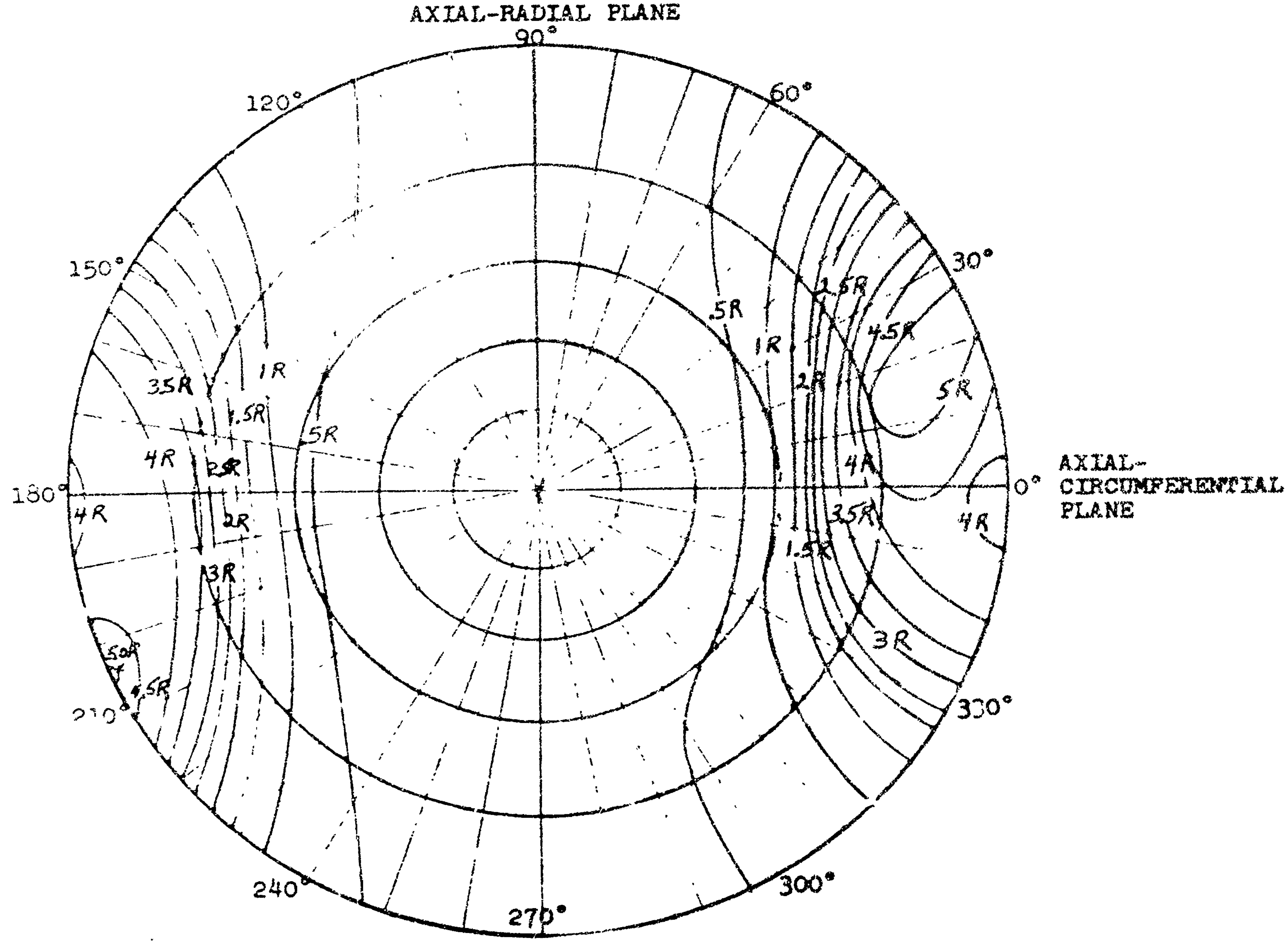


FIGURE 69

POLE FIGURE OF BASAL PLANE ORIENTATION FOR FORGING NO. 9

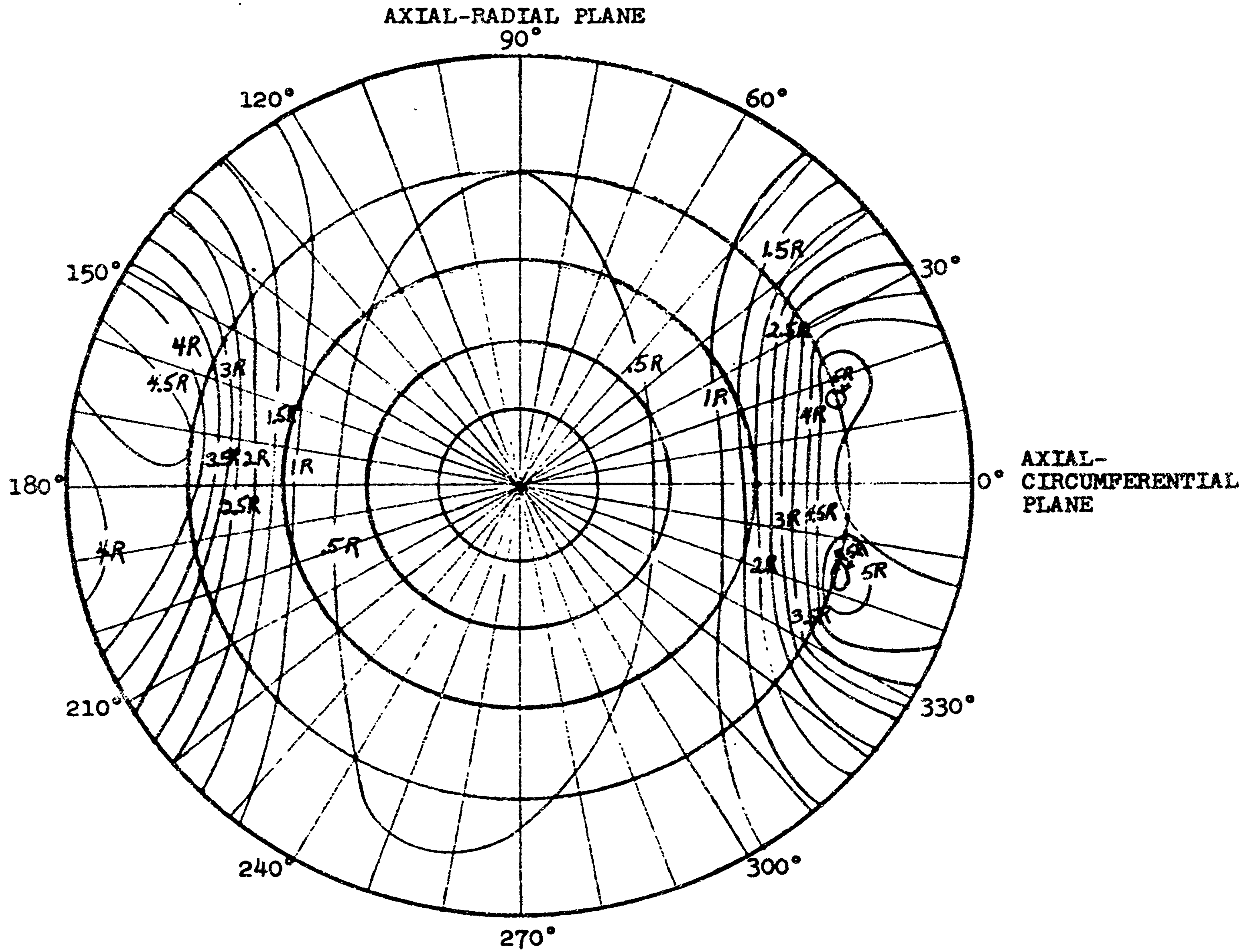


FIGURE 70

POLE FIGURE OF BASAL PLANE ORIENTATION FOR FORGING NO. 10

75-per-cent-upset-forged billet. It appeared, then, that the effect of back-extrusion upon a previously-upset-forged billet tended to reorient the preferred orientation from the radial-circumferential plane toward the axial-circumferential plane with little, if any, effect upon the magnitude of preferred orientation.

The resultant preferred orientation of Billet 6 closely approximated that of Billet 1. Both forgings had maximum values of 4R. Prior work[7] showed that a combination of forward-extrusion at a four-to-one ratio followed by a 60-per-cent-upset-forging operation produced a favorable balance of ductility and decreased the degree of preferred orientation to the extent that it approached that of vacuum-hot-pressed block. The two billets, therefore, had similar orientation prior to back-extrusion, so that similar orientation after back-extrusion could be expected. The influence of a decreased amount of initial forward-extrusion is shown in the pole figure for Forging 9, in which a maximum orientation of 5R was produced. Similarly, a decreased amount of forward-extrusion and an increased amount of upset-forging increased the maximum orientation to 5.5R, as shown in the pole figure for Forging 10, Figure 70.

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V. PHASE IV FULL-SCALE CONE DEVELOPMENT

A. Background

The model studies previously conducted on two-inch-diameter beryllium specimens and the limited success of the subscale cone-forming tryouts showed that the basic operation was technically feasible. However, the full-scale cone represented a significant size scale-up. Forming parameters for the subscale geometry had to be well established before proceeding with the full-scale cone.

The beryllium cone-forging program was therefore redirected toward further evaluating the following parameters on a subscale basis:

1. Wall thickness/diameter ratio;
2. Hydrostatic restraint;
3. Filler materials;
4. Preform shape.

A series of cone-forming trials was planned such that information received from each tryout could be applied to each successive tryout. This effort was aimed at establishing reliable cone-forming parameters as opposed to property optimization. With data on hand regarding the effects of various combinations of work upon properties, it was felt that forging sequences could be designed to meet property goals required by specific cone applications developing in the future.

To accomplish this work, a 20-inch-diameter by 16-1/4-inch-high B-102B vacuum-hot-pressed beryllium cylinder (Heat 3849) and an 8-1/4-inch-diameter by nine-inch-high cylinder (Heat 3770) were transferred from Contract AF33(615)-2231 to this contract, AF33(615)-1396. A portion of the 20-inch-diameter beryllium billet was reserved for forging the full-scale cone.

Specific geometries within a given shape classification often require the use of completely different forging methods. Recent interest had been directed toward beryllium cones having a length/diameter ratio approaching three-to-one. This geometry would suggest the use of a forging technique and die design which significantly differed from those used for a cone having a two-to-one height/diameter ratio. The height/diameter ratio is an important consideration when selecting a forging technique to produce a beryllium cone. Ratios of less than one-to-one have been produced by direct back-extrusion. This technique becomes impractical for cones having higher ratios due to tooling limitations. Use can then be made of the increase in height when a cylinder is converted into a cone of equal volume, as was done in the subscale tryouts. The problem then becomes one of producing a cylinder having sufficient length and desirable wall thickness from which a cone can be formed.

Future cone requirements were reviewed between cognizant Air Force personnel at Wright-Patterson Air Force Base and the Contractor. Based upon the ranges of dimensions described, the forging shape shown in Figure 71 was designed for the full-scale Phase IV part. The height/diameter ratio of approximately 3.4-to-one was twice that initially planned for the Phase IV part. Since back-extrusion is impractical for cylindrical beryllium shapes having height/diameter ratios beyond 1.5-to-one, a procedure for back-extrusion, forward-extrusion, and forming was selected.

B. Phase IV Material

The chemical compositions of the two lots of beryllium used for Phase IV of this program are shown in Table XXVII. The material was inspected for soundness using ultrasonic, macroetch, and dye-penetrant inspection techniques and was found to be satisfactory. Section size precluded radiographic inspection of the 20-inch-diameter billet. The 8-1/4-inch-diameter billet was inspected radiographically and was found to be free of significant indications of defects.

The larger billet was sectioned and machined into four 8-1/2-inch-diameter by five-inch-high billets and one 20-inch-diameter by ten-inch-high billet. The material was reinspected for flaws and found to be satisfactory.

During discussions of beryllium cone requirements, it was indicated that some cone designs are elastic modulus critical; others are strength critical. In view of these varying requirements, it appeared desirable to technically explore the use of cast beryllium for potential cost reduction for those applications which are mainly modulus critical. Dow Chemical Company's Rocky Flats Division shared this interest, and supplied several cast billets to include in the subscale cone-forming tryouts.

The billets were inspected at Ladish Co. using etching and dye-penetrant techniques and found to be free of significant defects. Ultrasonic inspection of cast beryllium for internal defects has been relatively ineffective because of the coarse-grained condition. Serial 10 did show the presence of some light surface tears which appeared to be associated with grain orientation. These billets were the highest-quality cast beryllium evaluated by Ladish Co.

C. Forging Activity on Subscale Cones

1. Extrusion Operation

Six vacuum-hot-pressed and three vacuum-cast beryllium billets were back-extruded into hollow cylinders 8-1/2 inches in diameter by 8-3/8 to 10-15/16 inches high. The cast beryllium billets were jacketed with 1/8-inch-thick mild steel in order to circum-

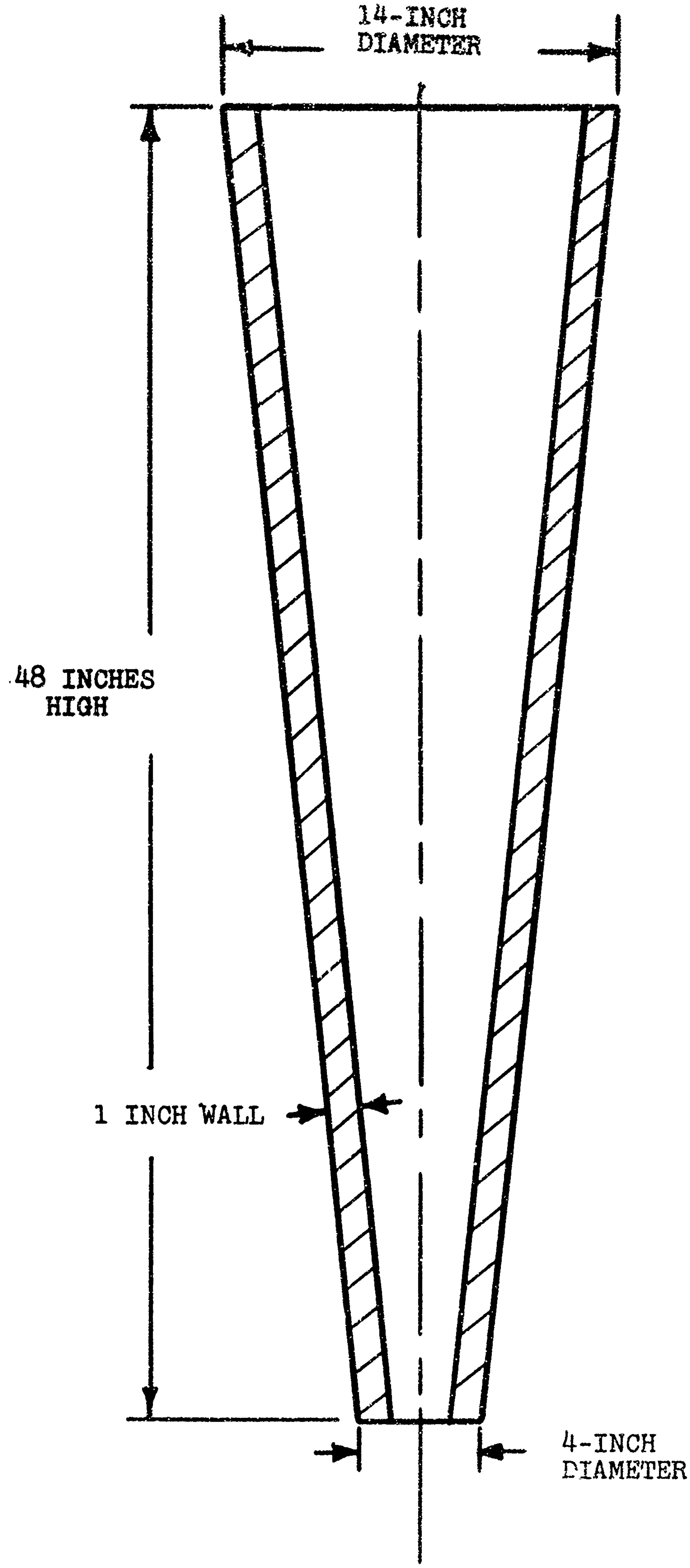

FIGURE 71

REDESIGNED
FULL-SCALE
CONE

TABLE XXVII

CHEMICAL COMPOSITIONS OF THE PHASE IV
B-102B BERYLLIUM MATERIAL

HEAT NO.	ELEMENT																	
	PER CENT		PARTS PER MILLION															
	Be	BeO	C	Al	Cr	Fe	Mg	Mn	Ni	Ti	Ag	Ca	Co	Cu	Mo	Pb	Si	Zn
3770	97.10	3.48	900	550	70	1328	20	115	120	180	4	85	4	65	8	6	300	55
3849	96.84	4.01	600	340	80	1140	130	65	130	170	3	85	8	70	10	6	100	55

vent toxicity hazards during heating. The tooling and procedure for back-extrusion were the same as those described earlier for the Phase III subscale cones. A more positive means for maintaining alignment between the punch and pot die had been incorporated into the tooling, in order to prevent abnormal punch shift during forging. The extrusion parameters used are shown in Table XXVIII.

A forging temperature of 1350°F was selected for the vacuum-hot-pressed billets since good forgeability is more reliably attained at this temperature. A higher forging temperature (1800°F) was used for the cast beryllium, in accordance with the recommendation from Dow Chemical Company, in order to minimize the occurrence of rupturing in the as-cast condition. Lower forging temperatures for cast beryllium can be employed after the cast structure is adequately refined and converted into a wrought structure having a minimum of 80 per cent reduction.[8]

All cylinders were successfully extruded with the exception of one of the cast billets, which developed several severe, isolated axial cracks running the length of the extrusion. Since the cast beryllium was jacketed and the jacket remained intact during the forging, lubrication problems should have been minimal. Also, since eight other billets, including two cast billets, were successfully extruded, it becomes difficult to trace the source of failure to forging effects. It is possible, however, that the amount of compressive support exerted on the cast beryllium during extrusion was marginal for this grade of material. On the other hand, if an undetected crack-type defect were present, it is most probable that the crack would have propagated during extrusion.

Photographs of the as-forged cylinders are presented in Figures 72 and 73. Dimensional inspection results are recorded in Table XXIX. All forgings except Serial 7 were inspected by ultrasonic techniques and found to be free of indications of internal defects. It must be noted, however, that the two cast cylinders were still relatively coarse and did not respond to ultrasonic inspection as satisfactorily as the vacuum-hot-pressed cylinders, so that the level of reliability of non-destructive testing data was not as high as desirable for the cast material.

2. Forming Operation

Serials 2 and 4 cylinders (vacuum-hot-pressed material) were machined to 8-1/4-inch-diameter by wall thicknesses of 0.700 and 0.500 inch, respectively. The cast-and-extruded beryllium, Serial 8, was machined and jacketed as shown in the drawing in Figure 74. Support discs were also prepared for forming the vacuum-hot-pressed extrusions. The technique planned for cone-forming is shown schematically in Figure 75. While the subscale cones are of a 1.5-to-one

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8 Frankeny, J. L. and Floyd, D. R., "Ingot Sheet Beryllium Fabrication," Dow Chemical Company Report on Contract AT(29-1)-1106, February 9, 1968

TABLE XXVIII

EXTRUSION PARAMETERS FOR 8-1/2-INCH DIAMETER SUBSCALE CYLINDERS

(Note: All cylinders were subjected to a post-forging thermal treatment of one hour at 1350°F.)

SERIAL IDENTITY	BERYLLIUM MATERIAL TYPE	LOT NO.	HEIGHT (INCHES)	BILLET TEMPERATURE (°F)	COMPRESSION RING TEMPERATURE (°F)	DIE TEMPERATURE (°F)
1	Vacuum-hot-pressed	3849	5	1350	1750	800 ± 100
2	Vacuum-hot-pressed	3849	5	1350	1750	800 ± 100
3	Vacuum-hot-pressed	3849	5	1350	1750	800 ± 100
4	Vacuum-hot-pressed	3849	5	1350	1750	800 ± 100
5	Vacuum-hot-pressed	3770	4-1/4	1350	1750	800 ± 100
6	Vacuum-hot-pressed	3770	4-1/4	1350	1750	800 ± 100
7	Arc-cast	828	5-1/4	1800	1750	800 ± 100
8	Arc-cast	834	5-1/4	1800	1750	800 ± 100
9	Arc-cast	859	5-1/4	1800	1750	800 ± 100

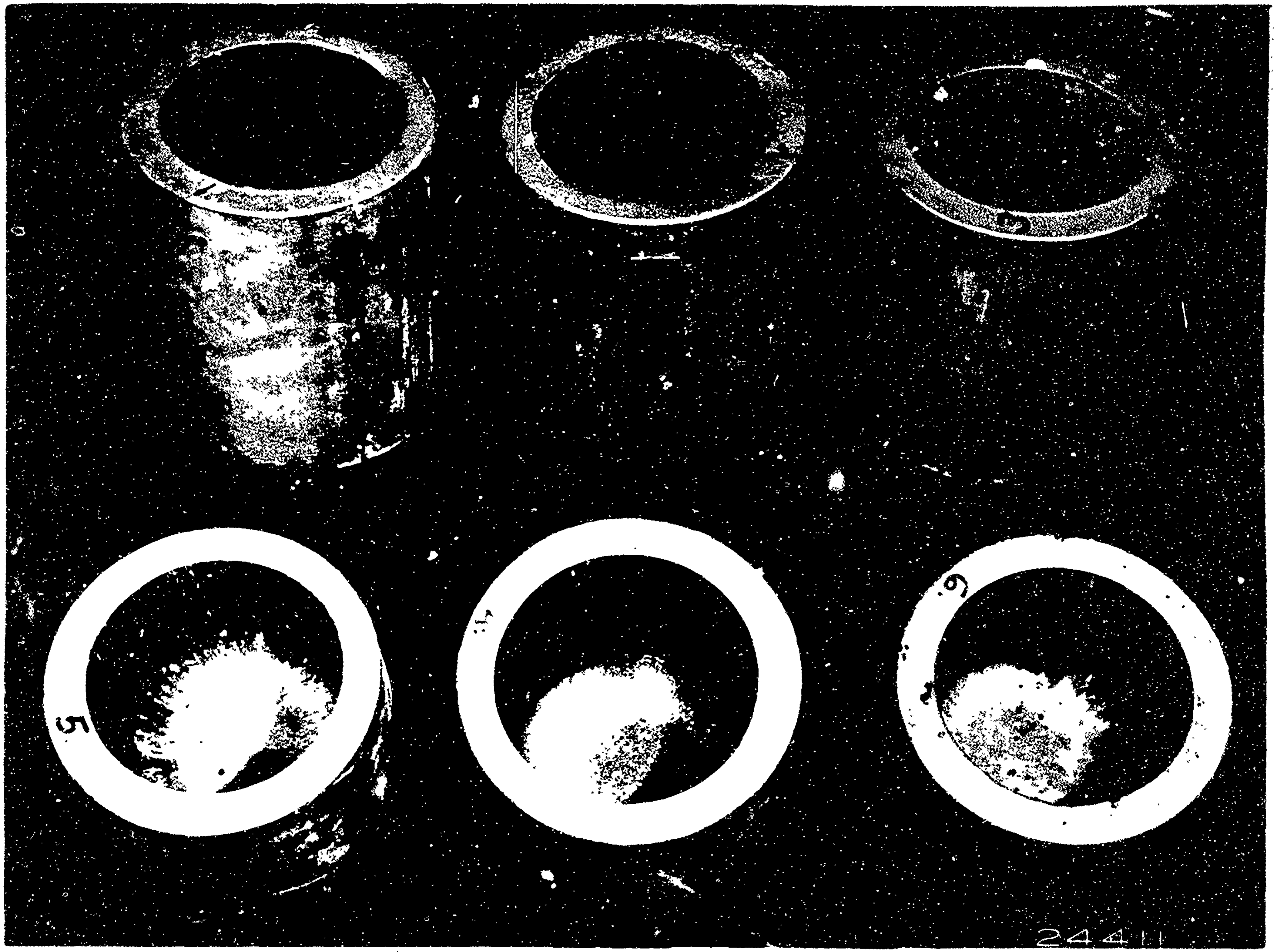


FIGURE 72
CYLINDERS EXTRUDED FROM VACUUM-HOT-PRESSED BERYLLIUM
SHOWN IN AS-FORGED CONDITION

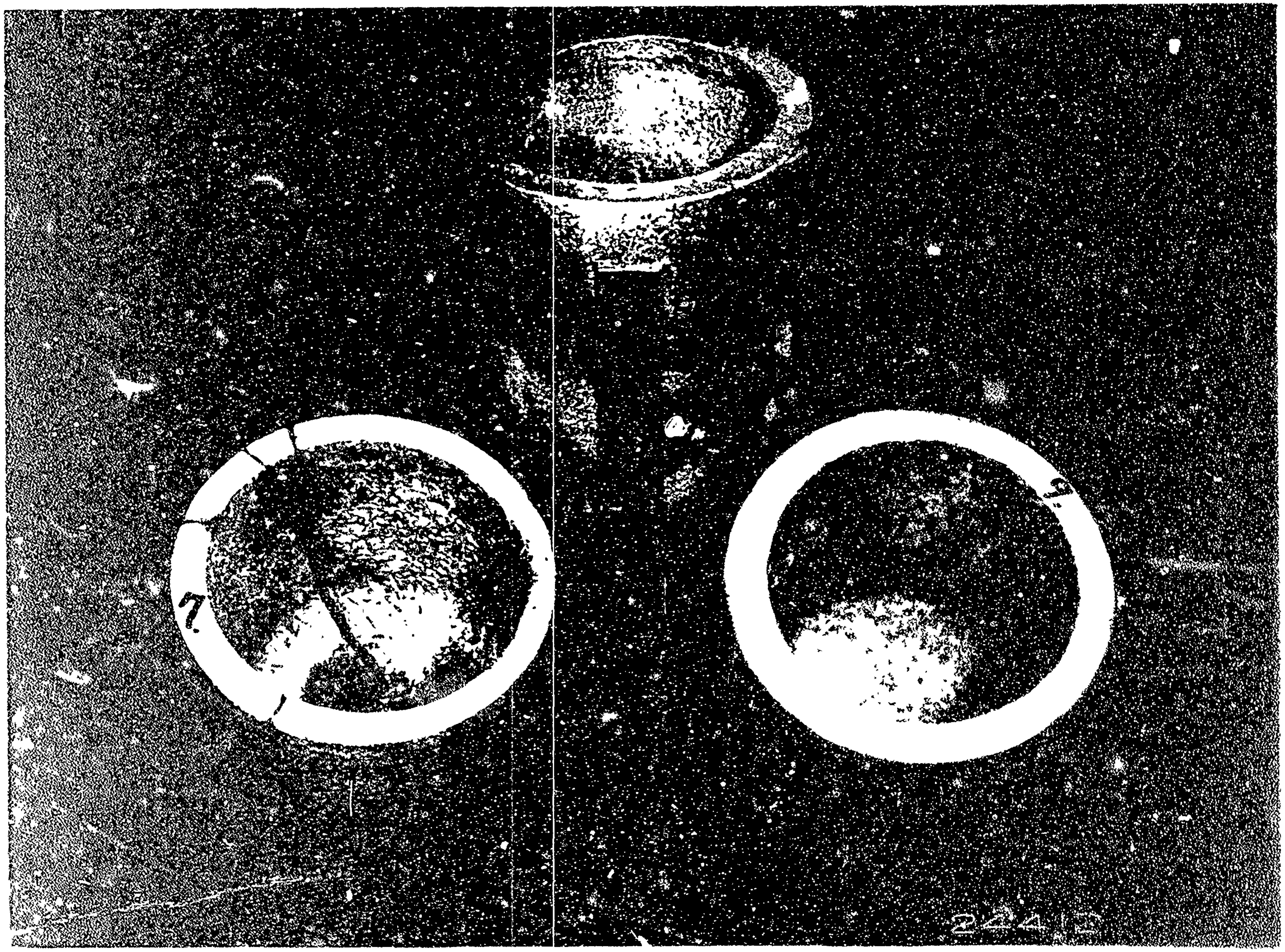


FIGURE 73

CYLINDERS EXTRUDED FROM ARC-CAST BERYLLIUM SHOWN IN THE AS-FORGED CONDITION

TABLE XXIX

DIMENSIONAL INSPECTION RESULTS OF BACK-EXTRUDED SUBSCALE CYLINDERS

(Note: All dimensions are in inches.)

SERIAL IDENTITY	HEIGHT RANGE		WALL THICKNESS RANGE (TOP LOCATION)		SLUG THICKNESS
1	10-15/16	11-3/16	1.110	0.970	13/16
2	10-9/16	10-13/16	1.100	0.980	13/16
3	10-3/8	10-7/16	1.100	1.000	1-5/16
4	10-1/16	10-1/2	1.110	0.960	1-1/2
5	8-3/8	8-9/16	1.140	0.960	3/4
6	8-9/16	8-11/16	1.100	0.990	9/16
7*	9-3/4	10-7/8	1.130	0.960	7/8
8	10-1/8	10-3/8	1.090	0.990	9/16
9	10-1/8	10-3/4	1.080	0.970	5/8

* Serial 7 had an axial crack.

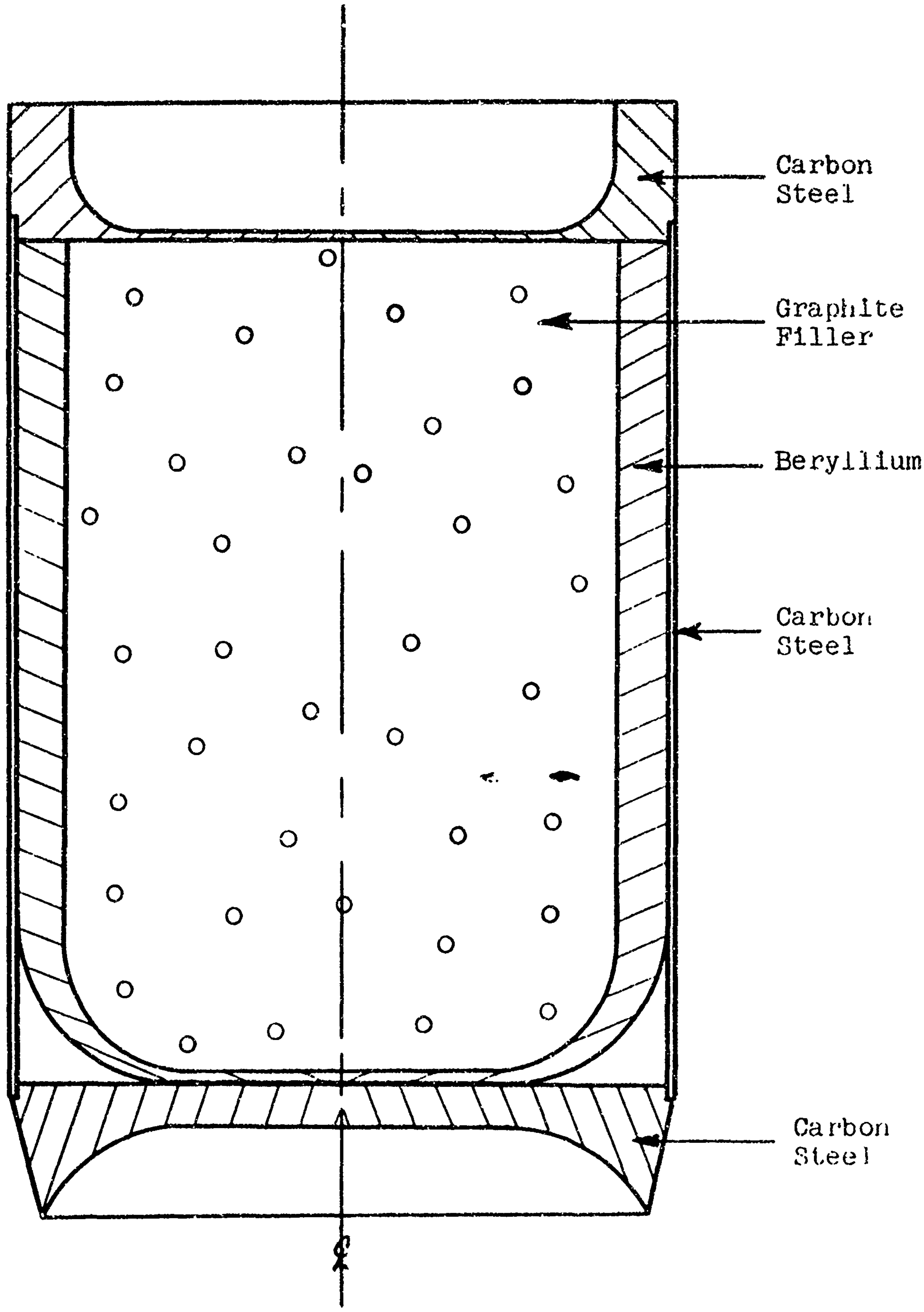


FIGURE 74

JACKETING ASSEMBLY FOR CAST-AND-EXTRUDED BERYLLIUM CYLINDER, SERIAL 8

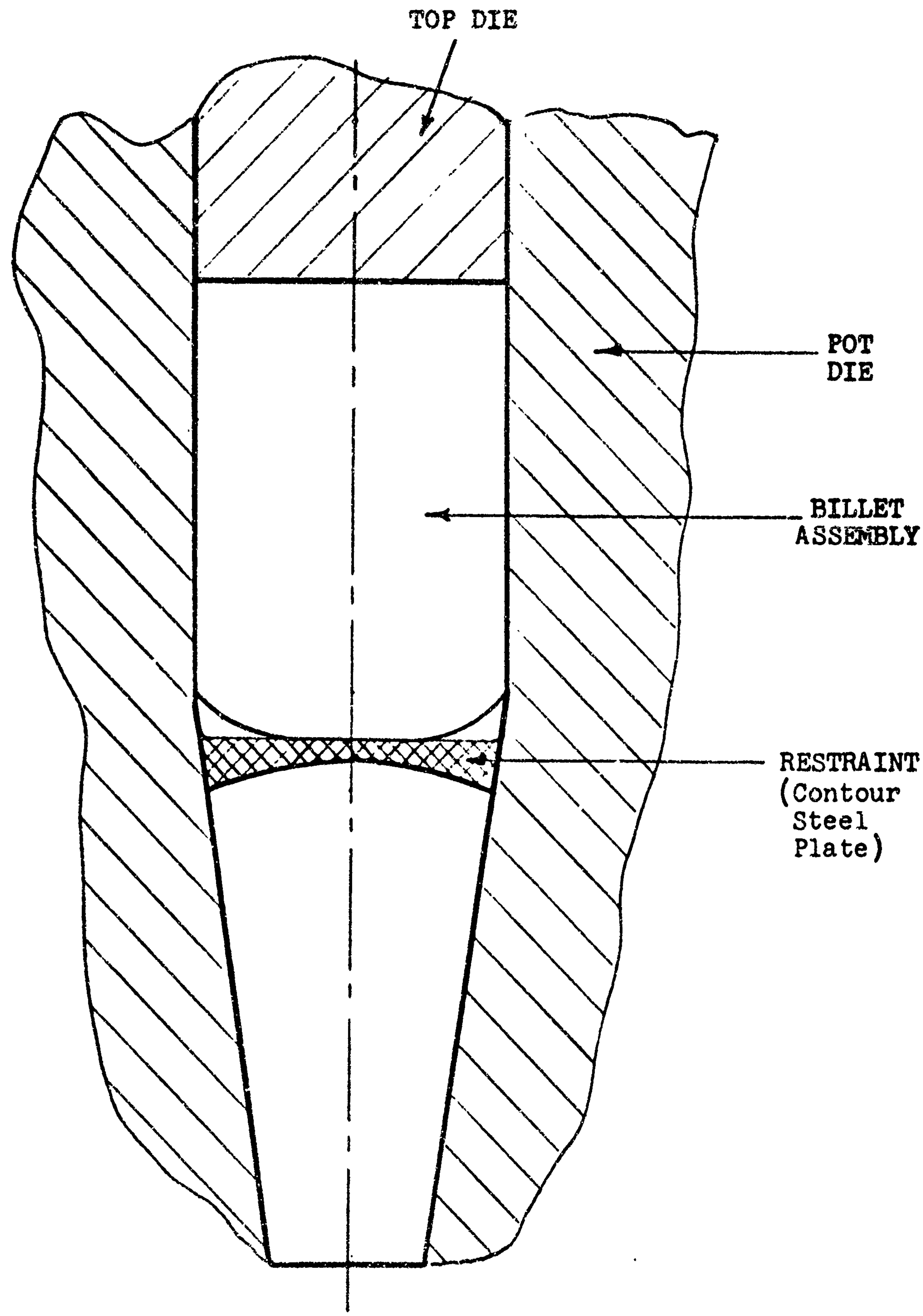


FIGURE 75

PROCEDURE FOR SUBSCALE CONE-FORMING OPERATION height/diameter ratio, the data developed can be used for manufacturing cones having higher height/diameter ratios. The finish-forged wall thickness for the full-scale cone was proportioned from the wall thickness determined from the subscale tryouts to be a minimum, but safe, value. The method and degree of restraint utilized was based upon the ability to provide adequate support with minimal interference with dimensional control. Filler material and temperature selection were based upon the ability to optimize dimensional control without adversely affecting formability.

The first tryout was aimed at establishing a workable range for wall thickness/diameter ratio. The three cone blanks were formed using graphite filler and the 1/2-inch-thick (center) contoured restraining discs. A forming temperature of 1350°F was used for extrusions made from vacuum-hot-pressed beryllium while a temperature of 1800°F was used for the cast beryllium blanks. The two cones produced from vacuum-hot-pressed beryllium (Serials 2 and 4) were completed successfully except that Serial 2 had a minor burst at the forward end. A photograph of the two cones appears in Figure 76. The cast beryllium (Serial 8) shattered during forming despite the use of a jacket. Difficulty was experienced in removing this part from the die after forming. It was not known whether fragments jammed the knockout or sticking occurred from other sources, resulting in the knockout causing the failure.

Since forming of the thinner-walled cone actually gave better results, the second tryout included two cylinders machined to wall thicknesses of 0.500 and 0.625 inch, respectively, to verify results. Restraint at the forward end was reduced from 1/2 to 1/4-inch thick. Graphite fillers and a forming temperature of 1350°F were again employed.

Cone Serial 2 formed in the first tryout was re-formed in the second tryout to increase height without using filler material. The second cast-and-extruded cylinder was formed in the second tryout using the same parameters as those used in the first tryout, except that both ends of the cylinder were open. The machined and etched blank is shown in Figure 77.

In this second tryout, all the cones produced from vacuum-hot-pressed material formed successfully except for minor tears and irregular shapes at the forward ends of Serials 1 and 5. These two cones are shown in Figure 78. The re-formed cone, Serial 2, which attained a height of 12 inches, is shown in Figure 79, where it is compared to the starting blank shape. The second vacuum-cast beryllium cylinder also shattered during forming. While it is believed that the blank formed satisfactorily, the jacket vents apparently sealed during forming or were inadequate for relieving internal pressure, so that catastrophic failure occurred during extraction from the die. The failure, therefore, was due to processing problems rather than material.

FIGURE 76: SUBSCALE CONES PRODUCED FROM VACUUM-HOT-PRESSED BERYLLIUM FORMED FROM CYLINDERS HAVING WALL THICKNESSES OF 0.700 INCH (SERIAL 2 - LEFT) AND 0.500 INCH (SERIAL 4 - RIGHT).

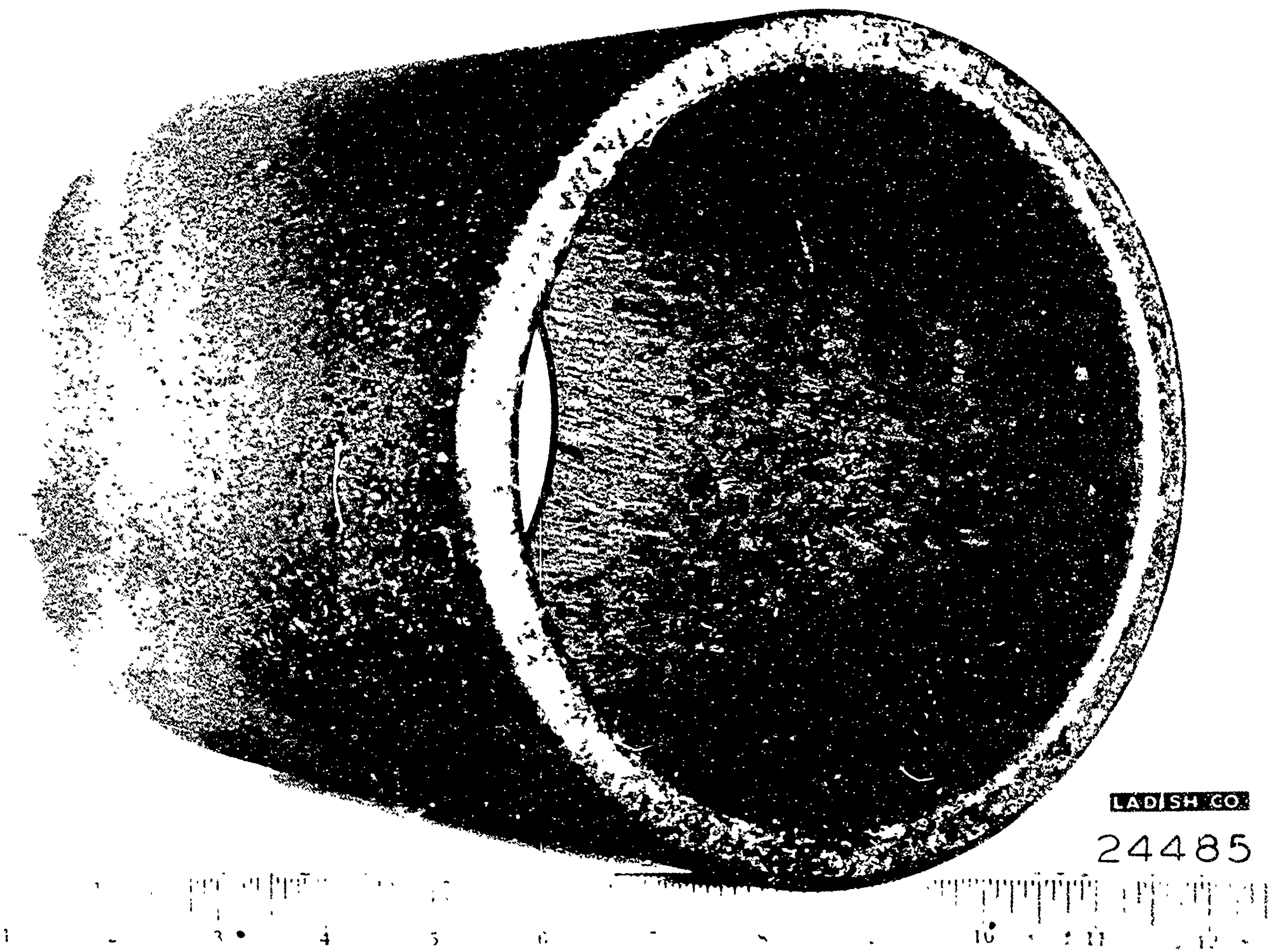


FIGURE 77: EXTRUDED AND MACHINED CYLINDER FORGED FROM CAST BERYLLIUM (ETCHED).

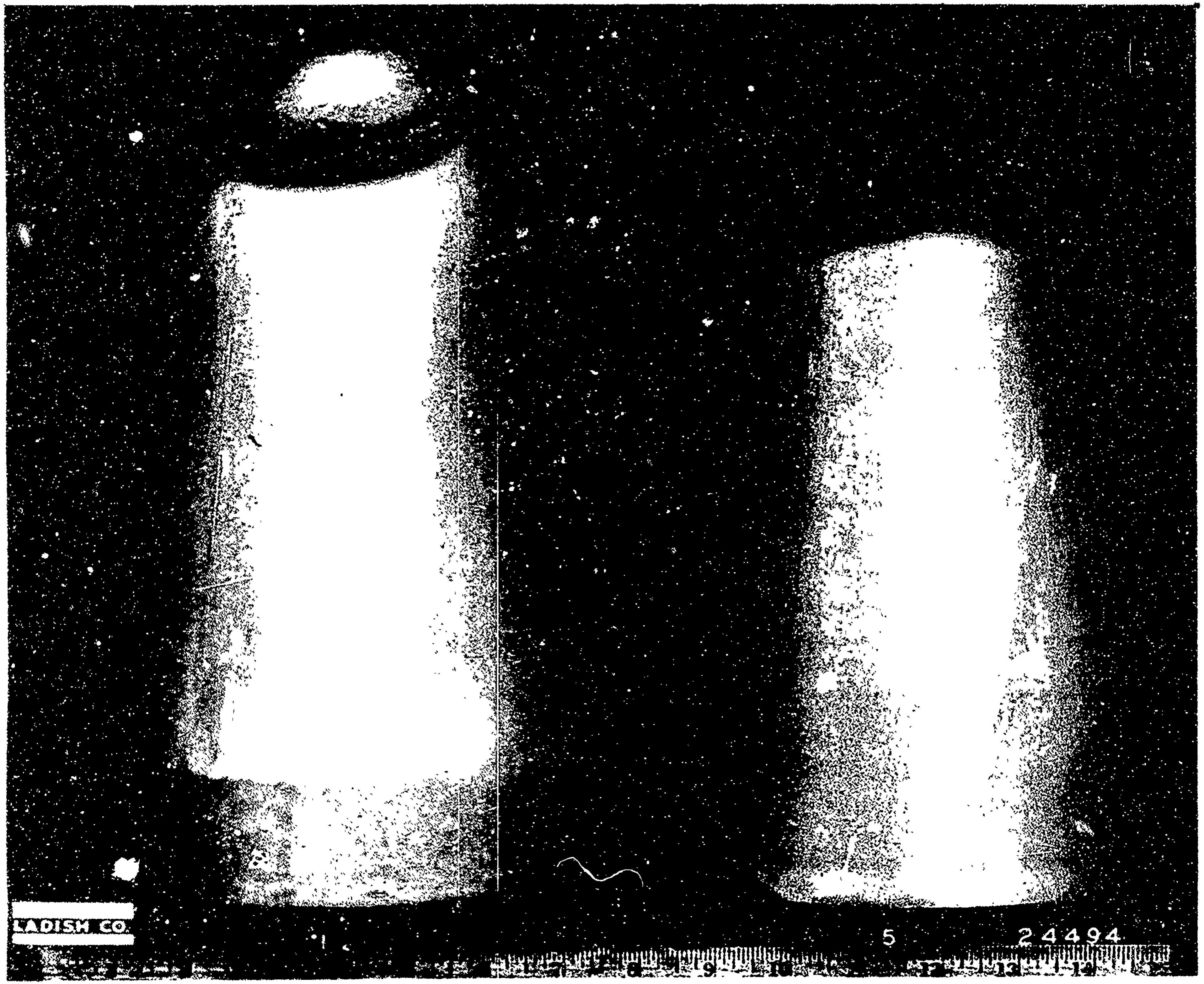


FIGURE 78: SUBSCALE CONES PRODUCED FROM VACUUM-HOT-PRESSED BERYLLIUM USING A REDUCED DEGREE OF RESTRAINT DURING FORMING.

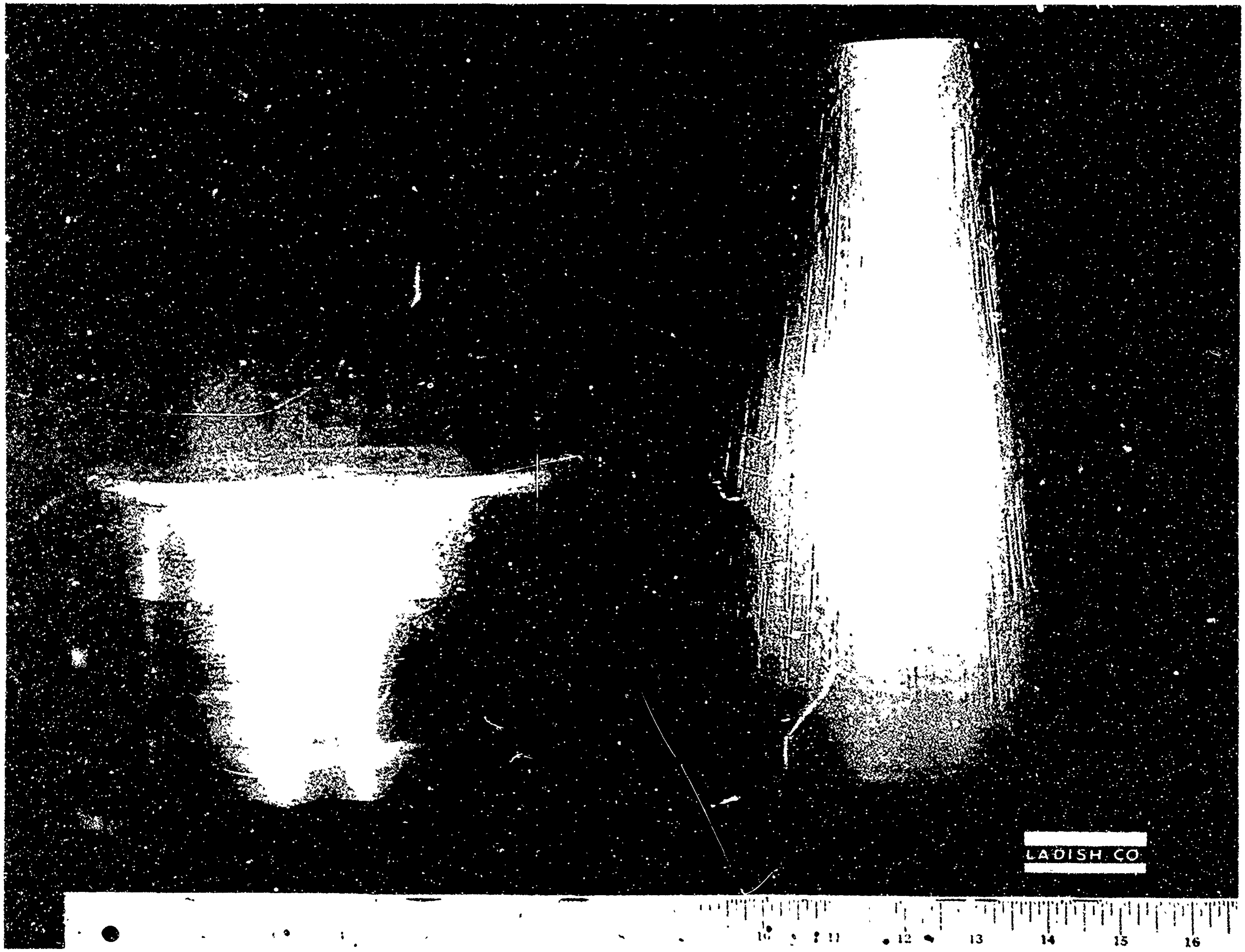


FIGURE 79: SUBSCALE CONE, SERIAL 2, AFTER SECOND FORMING OPERATION. PRODUCED FROM VACUUM-HOT-PRESSED CYLINDER HAVING SIZE SHOWN ON LEFT. (REFERENCE FIGURE 76)

Although the original plan for the subscale tryouts was to form cylinders having integral bottom slugs, which is the more severe type of forming, the program redirection toward a cone having a higher height/diameter ratio with both ends open made it desirable to include the forming of subscale cylinders (made from vacuum-hot-pressed beryllium) having both ends open. The last two subscale cylinders were, therefore, machined to wall thicknesses of 5/8 inch and were open on both ends. One blank used a graphite filler held in place by two steel plates and a center bolt. The other blank used a brass filler with brass plates welded to either end. Both blanks formed successfully and are shown in the photograph in Figure 80. The brass filler material produced a very smooth inner diameter surface.

Serial 1 was successfully re-formed without using filler material. This cone is shown in the photograph in Figure 81. Dimensional inspection results for all cones formed from the vacuum-hot-pressed material are shown in Table XXX.

The subscale tryouts were successful in establishing that wall thickness/diameter ratios in the range of .06 to .09 were adequate for cone-forming. Further, a negligible degree of restraint was required for the open-ended cylinders and both graphite and brass fillers effectively minimized wall thickening.

D. Model Studies of Cone-forming Techniques

The shift in interest from cones having a height/diameter ratio of 1.7-to-one to cones having ratios exceeding three-to-one altered the planned forging sequence since it became impractical to back-extrude cylinders having height/diameter ratios greater than 1.5-to-one. Development of a forging method to arrive at the longer shape could be approached either through significantly changing the forging technique or through including an additional step(s) in the original forging sequence. The former alternative would conceivably rely upon broader use of newer concepts or upscaled techniques and could introduce problems not readily predictable. However, it may have had desirable advantages, such as fewer steps, greater efficiency, and less tooling. The latter alternative had the distinct advantage of making more use of pertinent technical manufacturing data developed to date. In order to aid in the evaluation of a practical die design and forging sequence, a series of model studies was conducted using beryllium and other materials.

The specific objective of the model cone investigation, then, was to develop a practical technique for manufacturing a thin-walled beryllium cone having a height/diameter ratio of three-(or more)-to-one. Success at this level, combined with information from the subscale cone program, would provide data required for designing tooling for the full-scale Air Force cone (48 inches high by 14-inch major diameter by four-inch minor diameter by one-inch-thick wall).

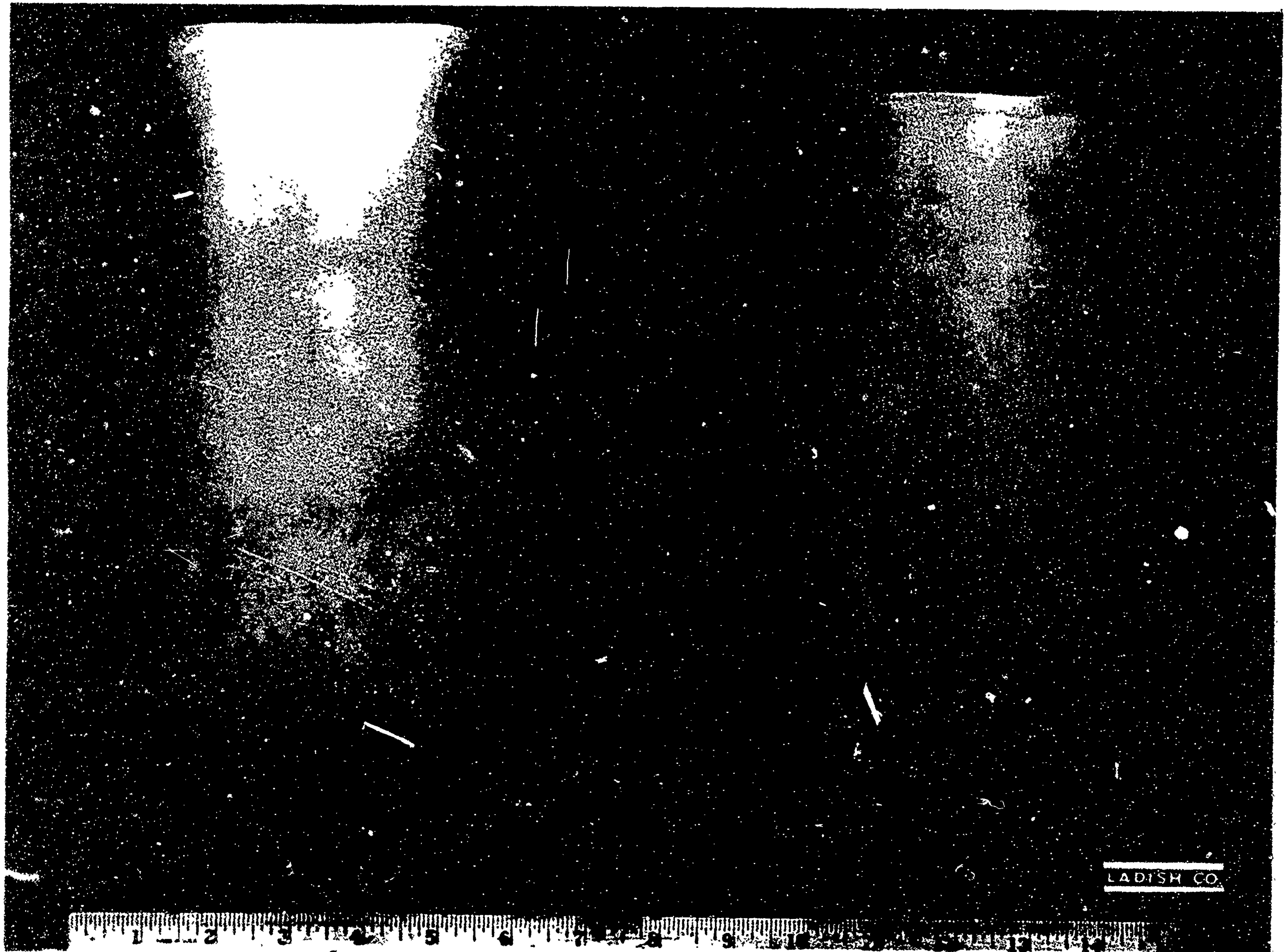


FIGURE 80: SUBSCALE CONES PRODUCED FROM VACUUM-HOT-PRESSED BERYLLIUM USINC FILL MATERIALS OF BRASS (SERIAL 3) AND GRAPHITE (SERIAL 6) FOR FORMING.

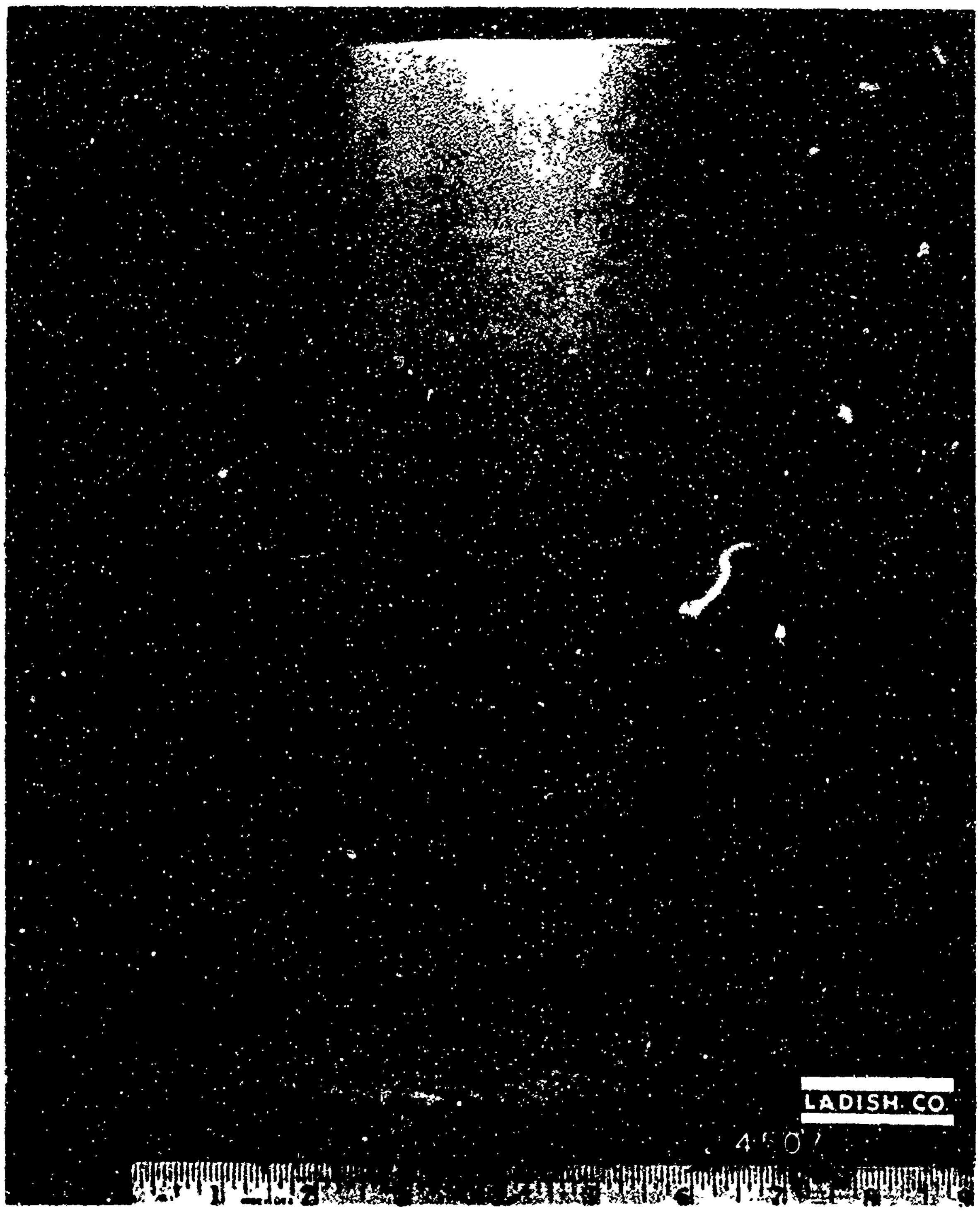


FIGURE 81

SUBSCALE CONE, SERIAL 1, AFTER SECOND FORMING OPERATION
(REFERENCE FIGURE 78)

TABLE XXX

WALL THICKNESS VARIATIONS IN FORMED SUBSCALE CONE FORGINGS

HEIGHT (IN INCHES) FROM MAJOR DIAMETER AT WHICH MEASUREMENTS WERE TAKEN	WALL THICKNESS (IN INCHES)							
	SERIAL 2-1 *	SERIAL 4	SERIAL 1-1 *	SERIAL 5	SERIAL 2-2 *	SERIAL 1-2 *	SERIAL 3	SERIAL 6
1/2	0.700	0.613	0.570	0.680	0.720	0.620	0.590	0.590
2-1/2	0.740	0.569	0.540	0.630	0.840	0.600	0.590	0.590
4-1/2	0.755	0.570	0.520	0.640	0.835	0.600	0.590	0.600
6-1/2	0.755	0.581	0.540	0.610	0.850	0.570	0.620	0.640
8-1/2	0.762	0.569	0.430	0.440	0.700	0.610	0.650	0.650
10-1/2	0.750	0.504	0.375		0.610	0.450	0.680	0.590
ORIGINAL CYLINDER THICKNESS	0.700	0.500	0.500	0.625			0.625	0.625

* The -1 refers to the first forming operation; the -2 to the second forming operation.

In order to achieve this goal, it was necessary to provide a technique wherein the solid cylindrical blank is converted into a long, hollow, thin-walled configuration suitable for forming into the above cone geometry. Wall reduction to the required thinness was the key problem. Attempts at producing a thin wall and concurrently forming into a conical shape were among the first methods tried in the model studies described. This concept entailed essentially the continuous forming of a cylinder and immediate conversion into a conical shape.

This first tryout incorporated forward-extruding beryllium cups directly into a cone die using a graphite block as a plastic mandrel for extrusion and filler for forming. A sketch of the tooling and operation is shown in Figure 82. Results of early trials showed that graphite was not suitable as a plastic mandrel, since wall thinning did not occur. In order to increase compressive forces against the inner diameter of the beryllium blank, a brass filler was used for the next trials. While some degree of thinning occurred toward the small end of the blank, the wall thickness was not uniform.

The beryllium cup shape was then jacketed, since this is the practice normally employed for forward-extrusion of beryllium. A back-up slug was also used to provide a means of pushing the beryllium completely through the die orifice. The blank assembly and results (sectioned) are shown in Figure 83. The height/diameter ratio of the cone produced was improved, but the walls were severely cracked. Confining the brass exerted a high pressure on the slug of the beryllium cup, which effectively maintained wall thickness after extrusion and during forming. However, this pressure, combined with a possible local shearing effect of the bottom corner of the cup against the jacket, may have caused the cracking.

The next trial took advantage of a cone geometry having both ends open. In this case, a hollow cylinder was jacketed and brass was used as the mandrel-filler. The billet and resultant cone are shown in Figure 84. It is apparent that the brass pushed ahead of the beryllium during extrusion and the cone produced was relatively thick-walled. A stiffer filler material of stainless steel was used as the mandrel-filler for the next trial. The pusher plate was integral with the mandrel. While a slightly greater degree of thinning occurred, it was insufficient to produce the desired reduction and the extrusion stalled before completion.

The filler approach and results did not appear to be positive enough to warrant additional effort for development into a technique for production of the 48-inch-high cone. The required compressive forces on the wall were not realized and the walls never thinned enough to produce a good height/diameter ratio. The filler method for forward-extrusion was replaced with a conventional forward-extrusion approach using an inner-diameter mandrel. A pusher ring was used to press the extruded cylinder into the cone-forming die stage by extruding behind the beryllium as shown in

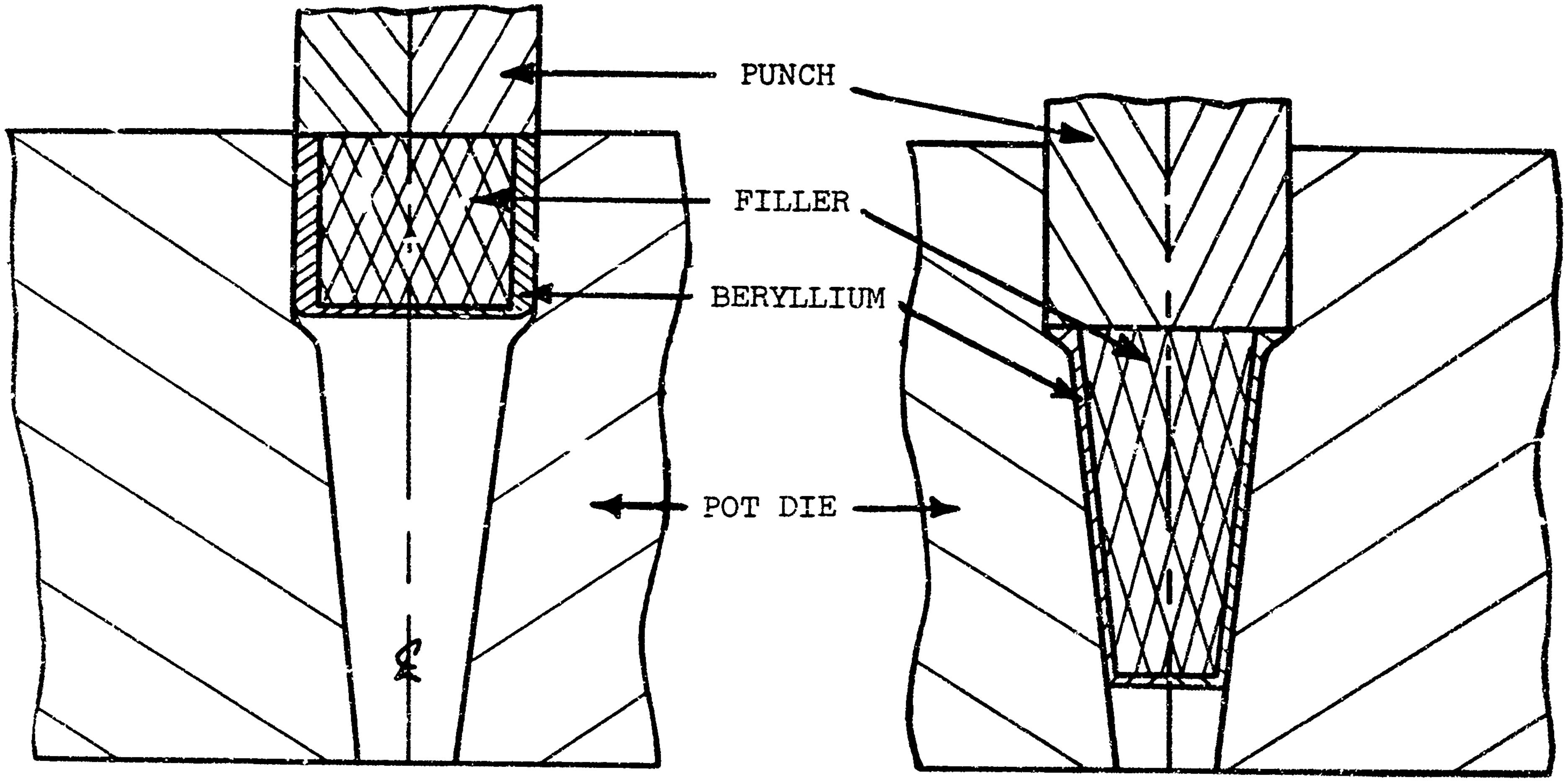
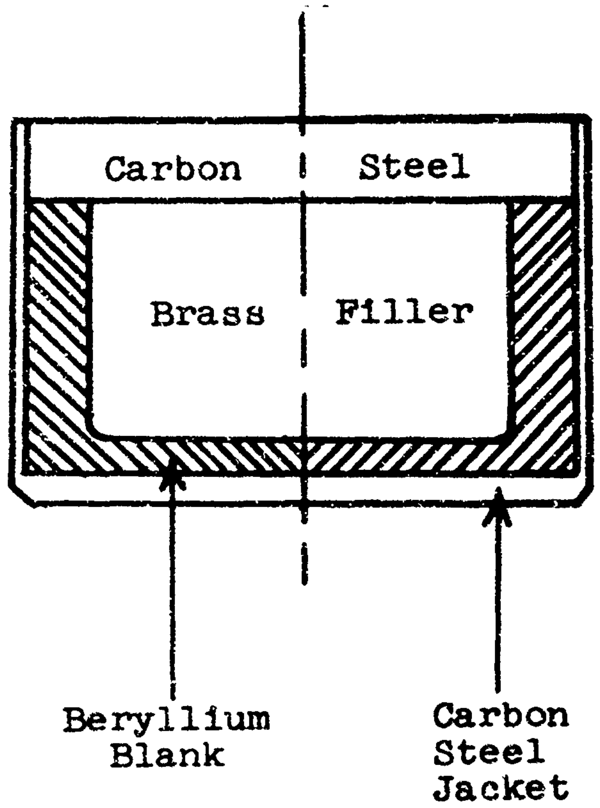


FIGURE 82

SCHEMATIC ILLUSTRATION OF MODEL STUDY FORMING OPERATION, COMBINING FORWARD EXTRUSION AND FORMING IN ONE OPERATION, AND USING DEFORMABLE MANDREL



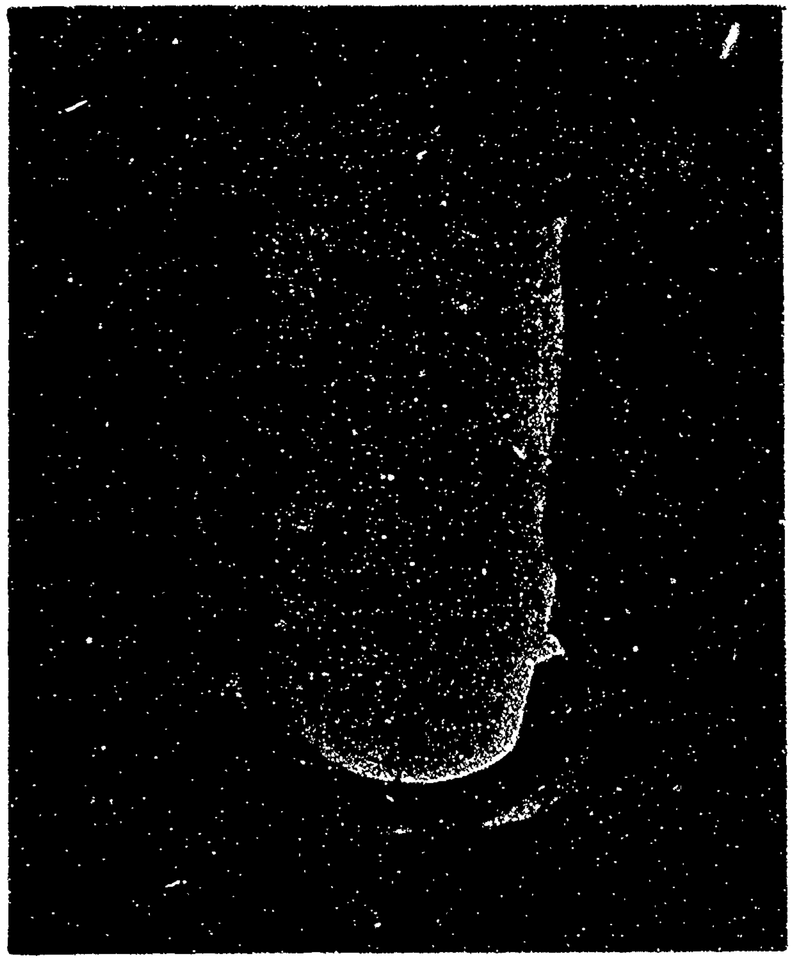
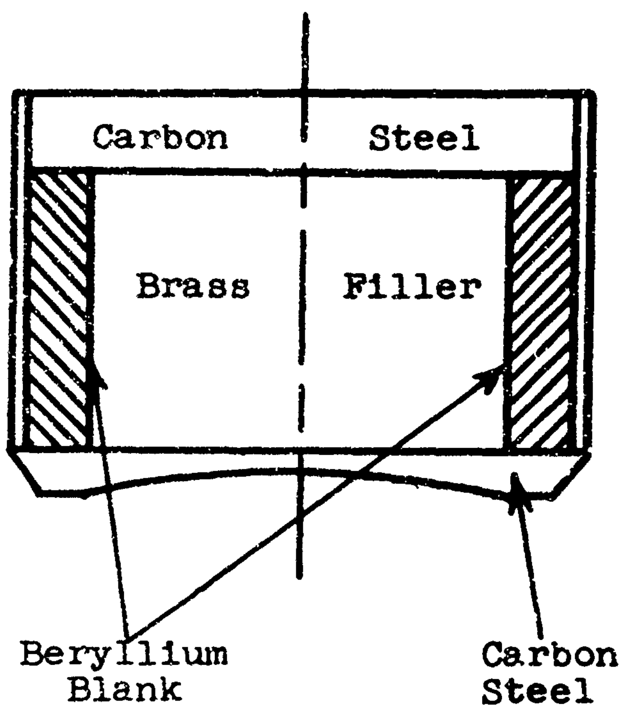


FIGURE 83

MODEL CONE FLOW STUDY SHOWING SKETCH OF STARTING ASSEMBLY AND PHOTOGRAPH OF SECTIONED FORMED BERYLLIUM CONE (REFERENCE FIGURE 82)



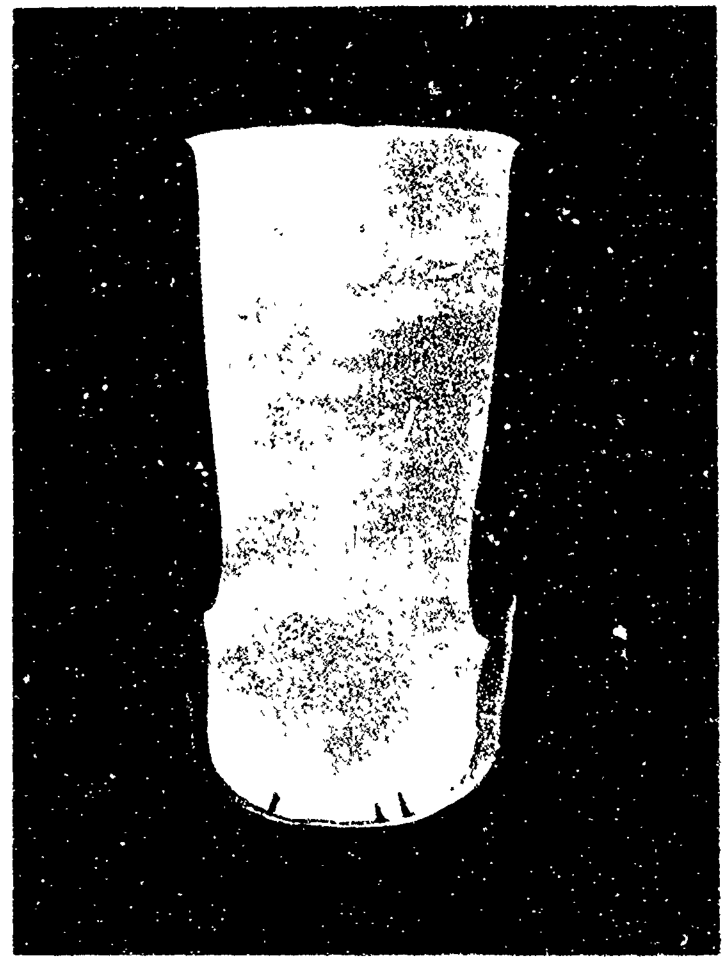


FIGURE 84

MODEL CONE FLOW STUDY SHOWING SKETCH OF STARTING ASSEMBLY AND PHOTOGRAPH OF SECTIONED FORMED BERYLLIUM CONE (REFERENCE FIGURE 82)

Figure 85. Carbon steel billets were used for the first tryouts. Lower temperatures (1400°F) completely stalled the extrusion. Partial extrusions were made at a temperature of 1800°F. Die chilling was rapid due to the thin billet assemblies. A beryllium billet was then extruded using the assembly shown in Figure 86. Again the forming was incomplete because of high restrictive back pressure and rapid die chilling, but a uniform, sound beryllium wall was obtained. An aluminum tryout was then extruded using die and material temperatures of 800°F and was formed to only 75 per cent of completion.

In view of the inability to extrude and form in one operation when using a material as soft as aluminum (and which is not subject to die chilling), it was decided the most practical approach for manufacturing the full-scale cone would include forward-extrusion as a separate operation.

E. Full-Scale Cone Trial

A processing sequence of back-extrusion, forward-extrusion, and forming was selected for forging the 20-inch-diameter by 10-1/4-inch-high billet into the 48-inch-long conical shape. The decision to forward-extrude as a separate operation resulted from the model studies which showed that considerable developmental work would be required before the feasibility of a combined forward-extrude-and-form approach was established. Thus, the selected forging sequence involved back-extruding the billet into a 19-1/2-inch-diameter by 11-3/4-inch inner diameter by 15-inch-high cylinder using compressive restraint; forward-extruding into a 14-inch outer diameter by 12-inch inner diameter by 44-inch-long tube; then forming to the required conical shape. The sequence is shown schematically in Figure 87.

The back-extrusion operation was based upon previously established procedures. The specific tooling used is shown in Figure 88. The tooling, compression ring, and beryllium were heated to temperatures of 800, 1750, and 1350°F, respectively. No difficulties occurred during the actual operation. However, a severe outer diameter tear was evident after extraction from the dies. The rupture extended from the outer diameter to within 1/2 inch of the inner diameter. The defect is shown in Figure 89. Since there was no evidence of lubrication breakdown and the tooling responded well, the adequacy of the degree of restraint used has been questioned. It is believed that, at some point during back extrusion the support imparted to the beryllium was critically reduced due to the mode of collapse of the hot steel ring, thus permitting rupturing to occur. Because only one billet was involved, there was no opportunity to modify the restraint ring and further evaluate the cause.

The defect was removed by parting off the top four inches of the cylinder. Inspection of the billet after machining the inner and outer diameters showed that extensive tight cracks were also

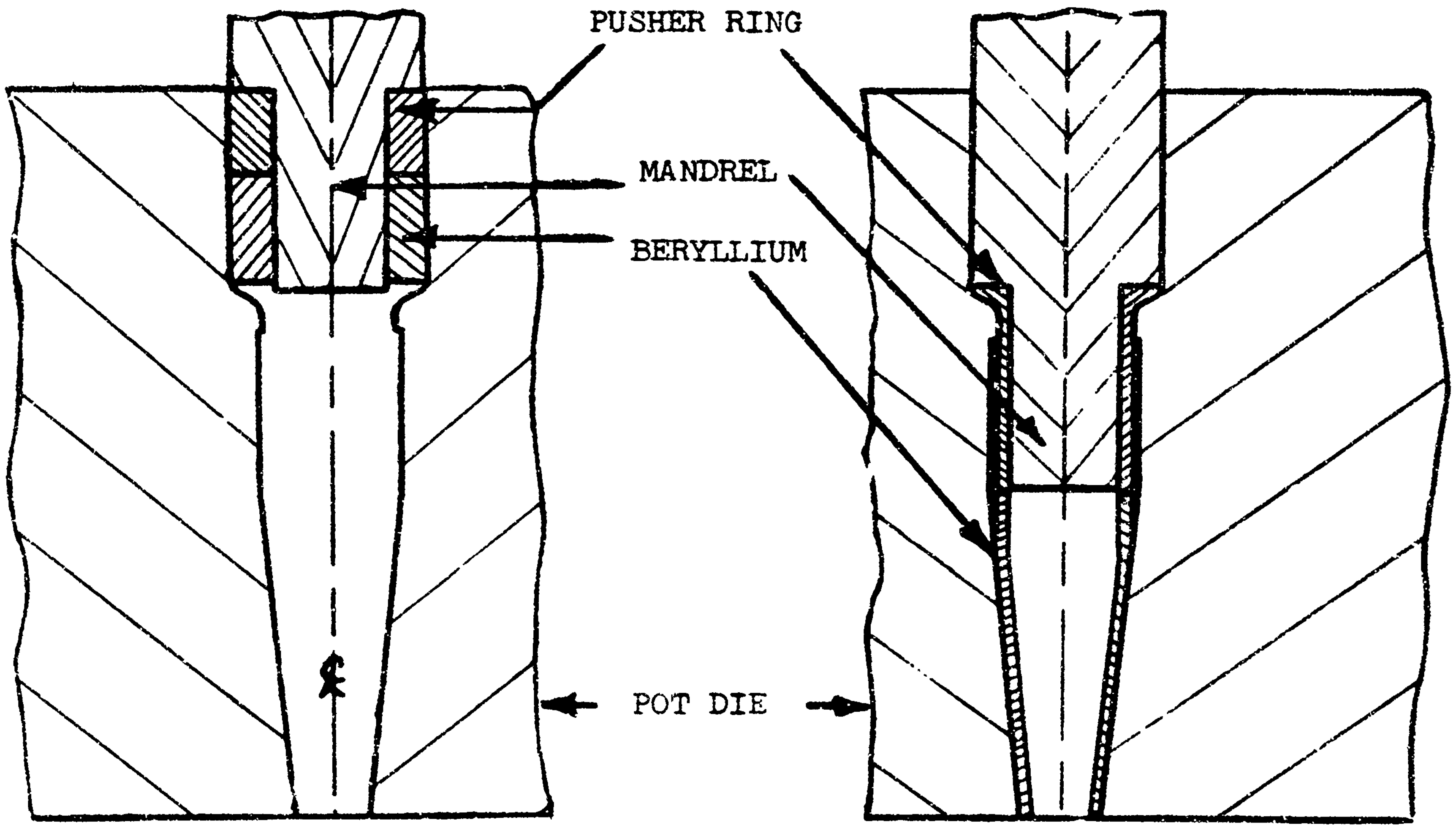


FIGURE 85

SCHEMATIC ILLUSTRATION OF MODEL STUDY FORMING OPERATION, COMBINING FORWARD EXTRUSION AND FORMING INTO ONE OPERATION, AND USING RIGID MANDREL

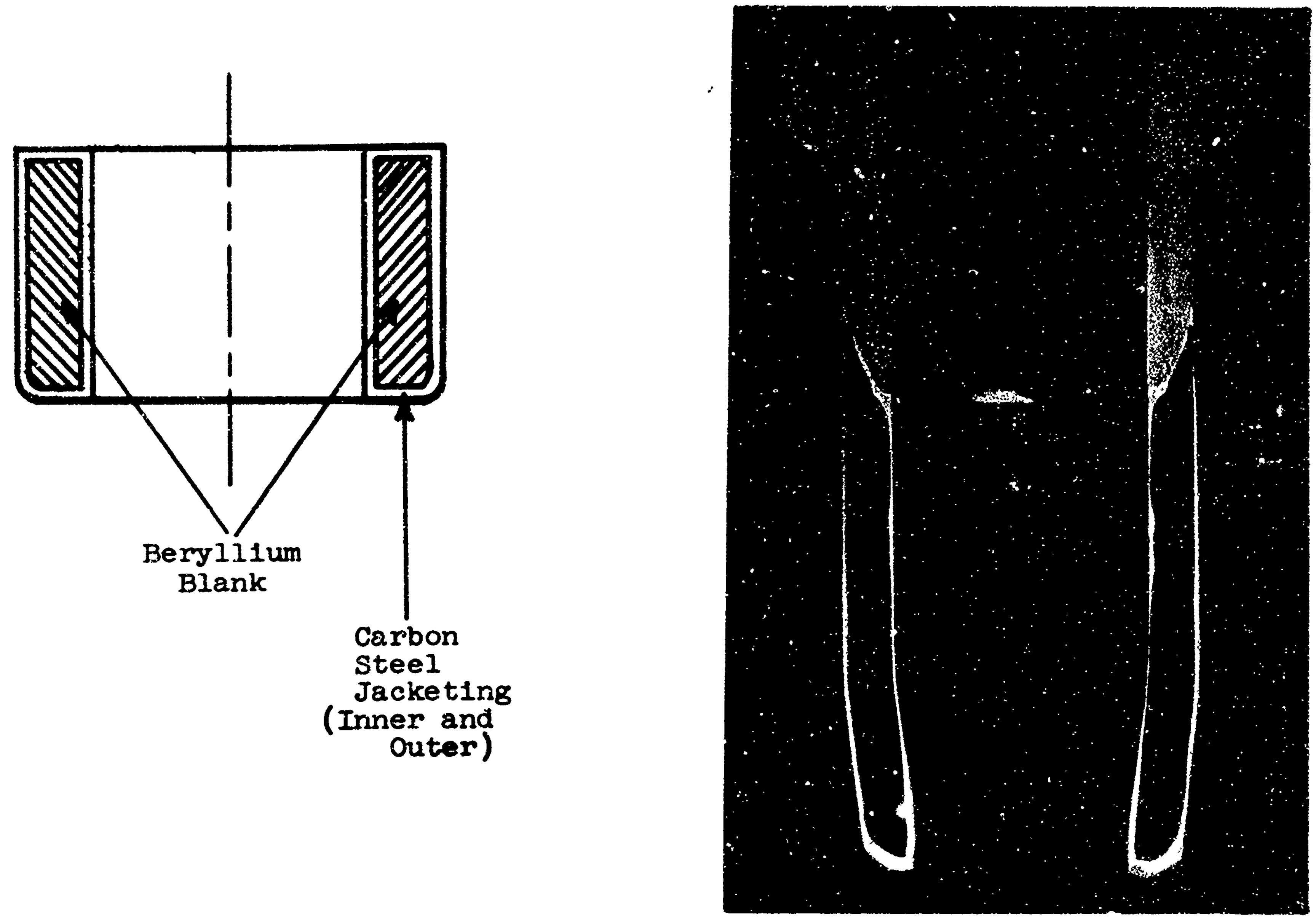


FIGURE 86

MODEL CONE FLOW STUDY SHOWING SKETCH OF STARTING ASSEMBLY AND PHOTOGRAPH OF SECTIONED FORMED BERYLLIUM CONE (REFERENCE FIGURE 85)

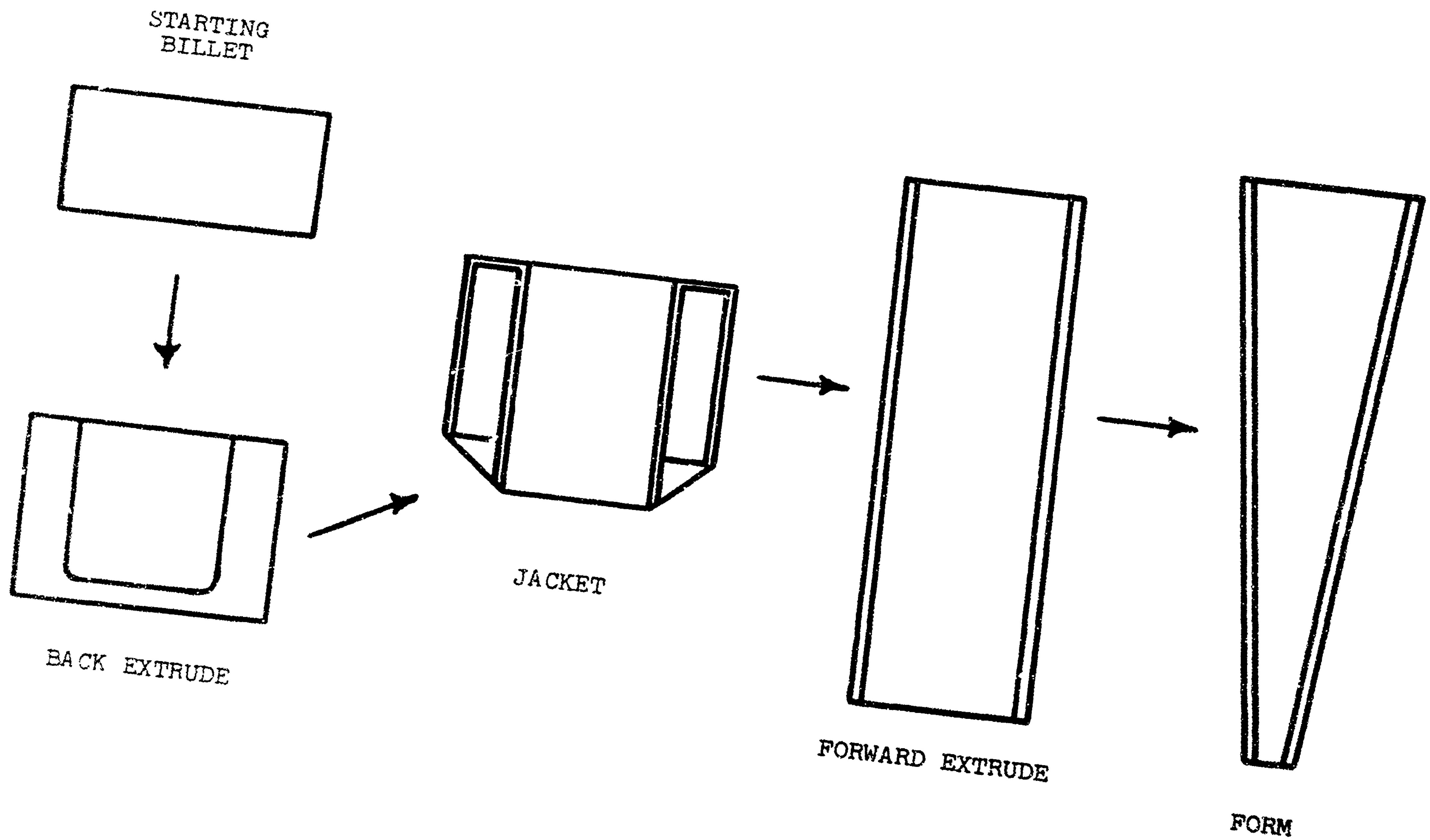


FIGURE 87
FORGING SEQUENCE FOR THE PHASE IV FULL-SCALE BERYLLIUM CONE

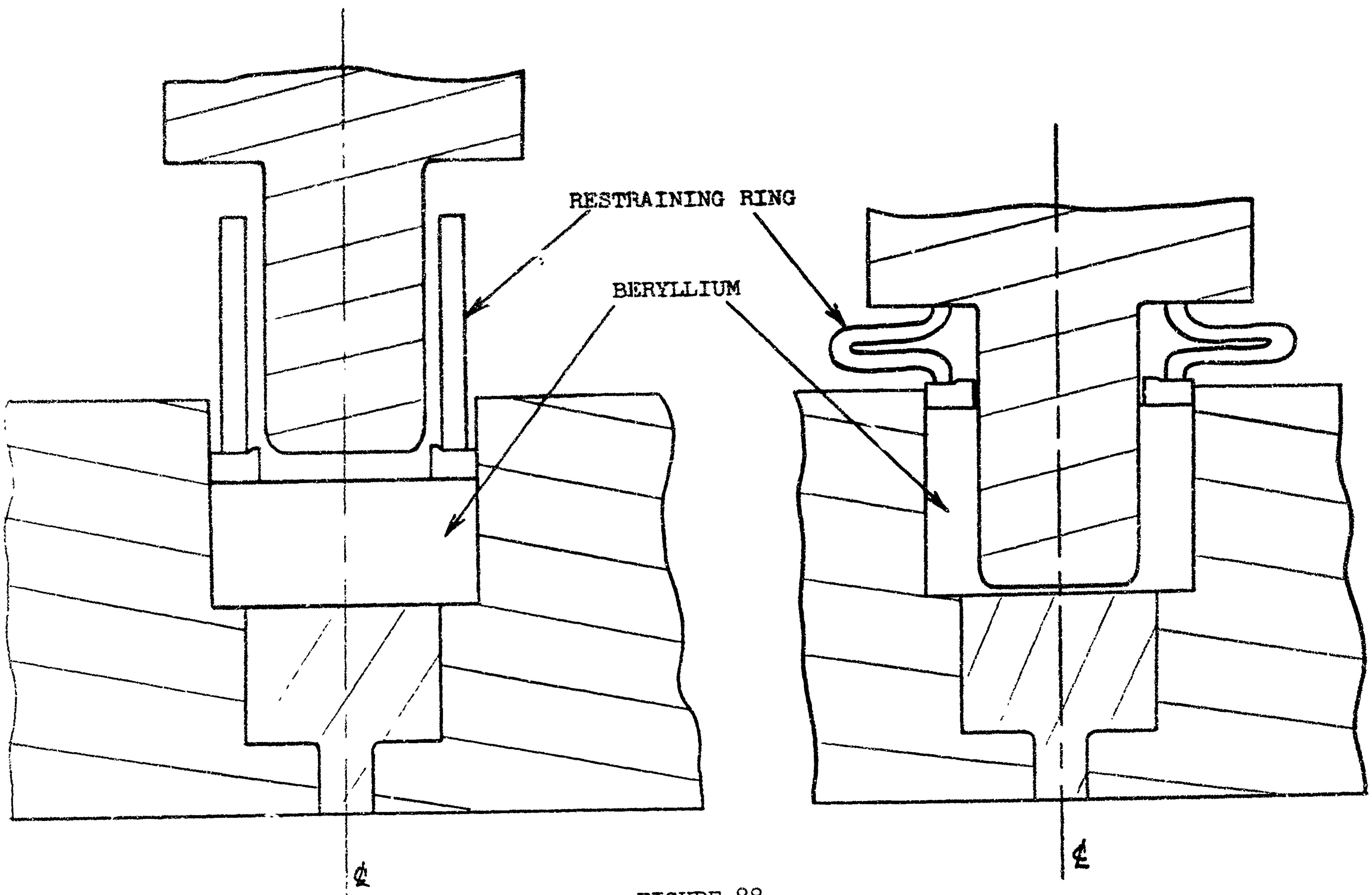


FIGURE 88

TOOLING ARRANGEMENT FOR THE FULL-SCALE CONE BACK-EXTRUSION OPERATION

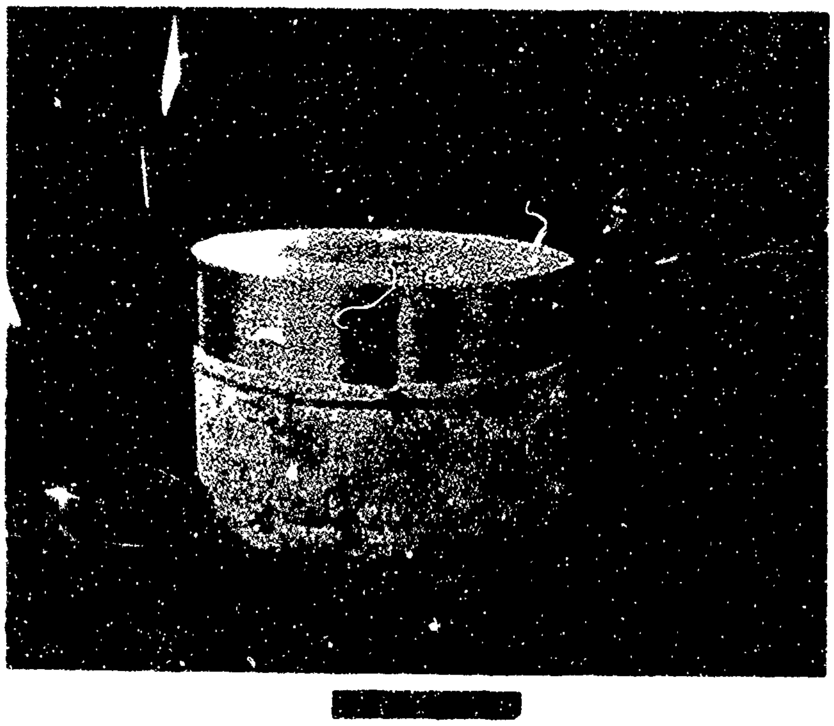


FIGURE 89

THE BACK-EXTRUDED BERYLLIUM CYLINDER SHOWING
THE OUTER-DIAMETER TEAR

present throughout both sections. These cracks traveled in an axial direction and extended to half the height of the larger section of the cylinder. The two machined sections are shown in Figure 90. Since the beryllium structure was only moderately altered from that of the vacuum-hot-pressed condition at this stage, and since the next operation entailed complete jacketing of the beryllium, it was decided to attempt repair by diffusion bonding during the forward-extrusion operation. The two sections were assembled into a jacket consisting of mild steel on the outer diameter and stainless steel on the inner diameter. The assembly was then evacuated, heated to 1200°F for 72 hours, and sealed.

The forward-extrusion operation and tooling were patterned after the design developed during prior programs,[9] but they represented a significant scale-up in size. The tooling assembly is shown in Figure 91. The jacketed and evacuated billet assembly was forward-extruded at 1350°F to the 14-1/2-inch-diameter by 40-inch-long beryllium cylinder shown in Figure 92. While the two beryllium sections encased in the evacuated assembly were successfully bonded, new defects developed during the extrusion. Circumferential hot tears occurred on the inner diameter and tight, deep, axial cracks occurred along the length. The primary failure started with tearing of the inner diameter stainless steel jacket adjacent to the forward section of the beryllium. Beryllium failure began behind this point in a circumferential direction. The initial jacket rupture thereby caused interference in the flow of the beryllium as evidenced by the development of a wavy surface on the inner diameter of beryllium. The inner diameter jacket extruded and ruptured circumferentially at intervals of approximately six inches. This caused the beryllium to extrude intermittently over or with the stainless steel jacket, resulting in the circumferential hot tears.

The axial crack apparently occurred after the extrusion passed through the die orifice, at which point the extrusion outer diameter was no longer supported. Whether failure occurred as extrusion progressed or during extraction of the punch from the assembly is not known. The ruptured sections of the inner diameter jacket which had to be extracted from the punch did so by being pushed against the wavy surfaces of the beryllium. This wedge action developed circumferential tensile stresses in the beryllium cylinder, which could account for the axial cracks. Based upon past experience in forging beryllium and examination of this extruded cylinder, it appears that the initial jacket failure led to the eventual occurrence of both types of defects.

The axial defects extended through the wall and, therefore, precluded completion of the forming operation. However, the forming concept was proved practical during the subscale trials, thereby enabling production of forged beryllium cones by using the basic techniques developed in this program.

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9 Hayes, A. F., "Beryllium Forgings for Turbine Engine Components," Technical Report AFML-TR-67-334, Ladish Co. under Contract AF33(615)-2231, October 1967

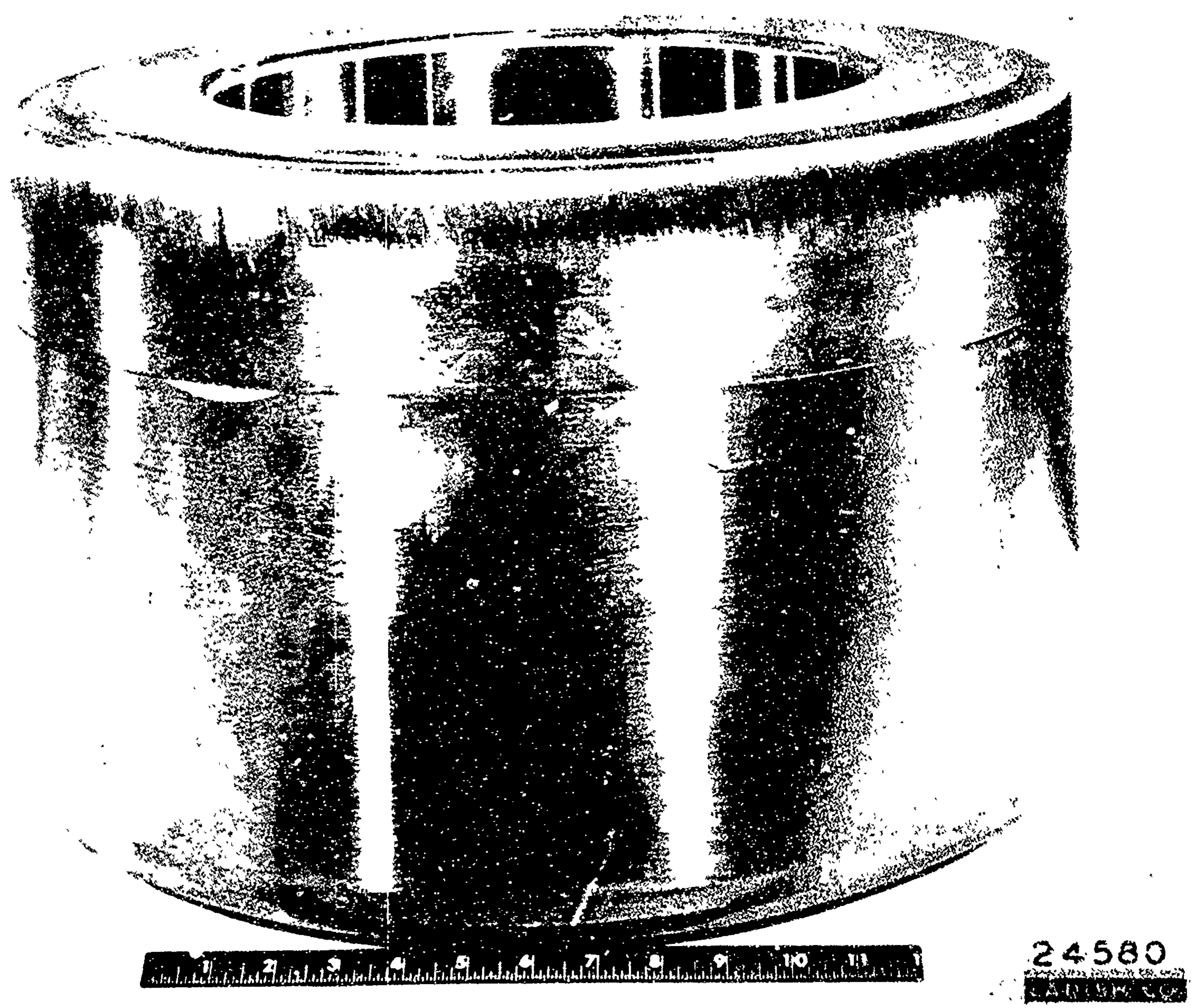


FIGURE 90: BACK-EXTRUDED AND MACHINED CYLINDER SHOWING DEFECT PARTED OUT.

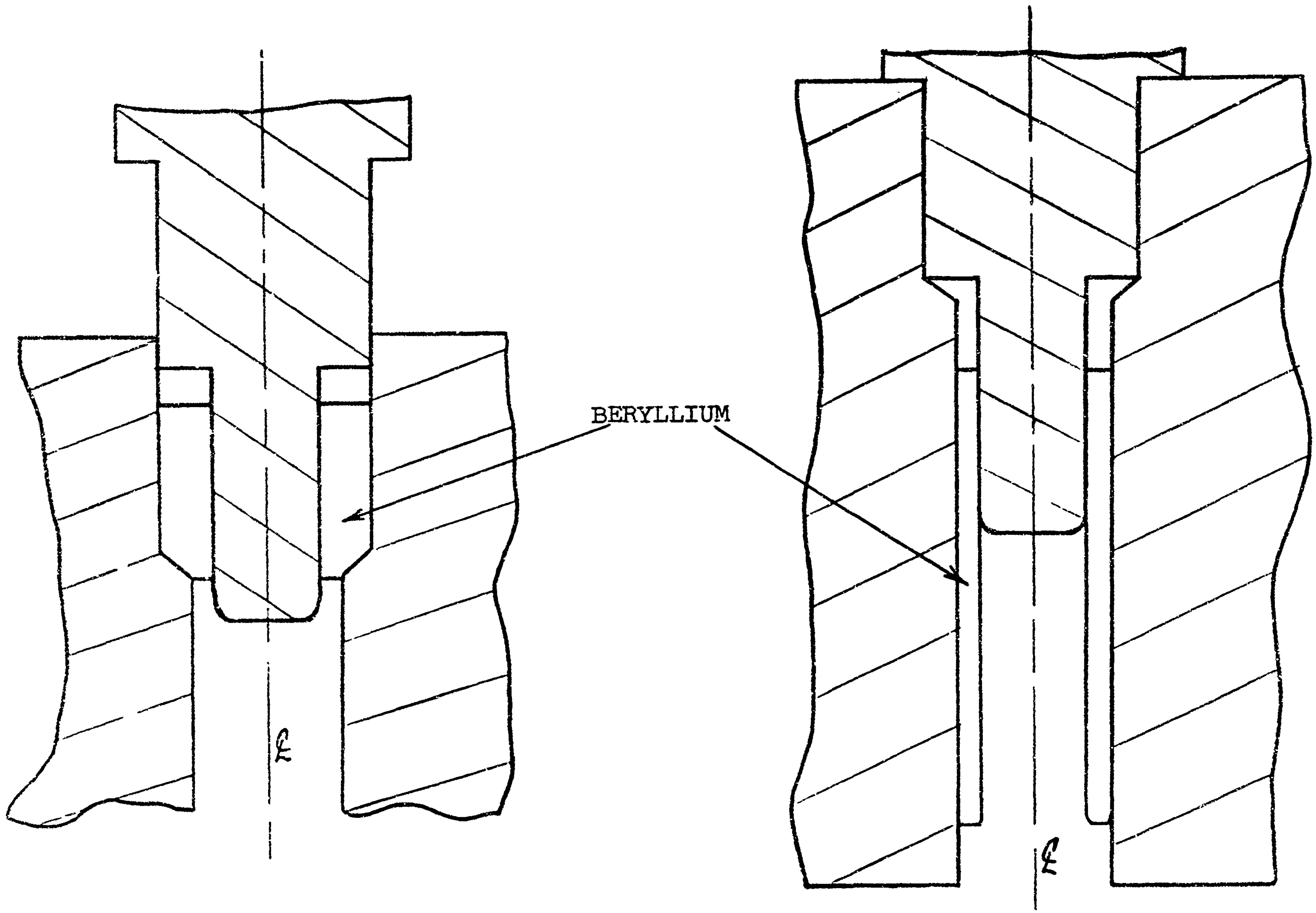


FIGURE 91

TOOLING ARRANGEMENT FOR THE FULL-SCALE CONE FORWARD EXTRUSION OPERATION

FIGURE 92

FORWARD-EXTRUDED BERYLLIUM FOR THE

FULL-SCALE CONE

Tensile properties were determined at the forward and aft ends of the cylinder in both axial and circumferential directions. Tensile specimens were also removed from the bond interface section and tested. The results of the tests are shown in Table XXXI. Yield strength exceeded 75 Ksi under all conditions tested and the target goal of 80 Ksi was almost attained except for two tests with values of 79 Ksi. Elongation varied considerably, again demonstrating the marked effects of test direction and the relative degree of deformation. Since the cone-forming operation entails a milder degree of deformation, the properties developed in a complete cone would not be expected to vary drastically from those attained in the cylinder tested.

TABLE XXXI

ROOM-TEMPERATURE TENSILE PROPERTIES OF THE 14-1/2-INCH-DIAMETER BY 40-INCH-LONG BERYLLIUM CYLINDER FORGING

TEST LOCATION	TEST DIRECTION	0.2% OFFSET YIELD STRENGTH (KSI)	ULTIMATE STRENGTH (KSI)	ELONGATION (PER CENT)	REDUCTION IN AREA (PER CENT)
Aft - O.D.	Circ.*	81.7	94.7	2.0	2.0
Aft - I.D.	Circ.	83.3	98.5	3.0	3.0
Aft - O.D.	Axial	85.1	120.8	11.0	13.0
Aft - I.D.	Axial	84.4	119.1	10.0	10.0
Forward-O.D.	Circ.	78.6	98.5	5.0	5.0
Forward-I.D.	Circ.	83.5	103.2	17.0	20.0
Forward-O.D.	Axial	79.2	108.3	11.0	13.0
Forward-I.D.	Axial	87.5	105.2	23.0	25.0
Bond	Axial	93.3	125.2	9.0	9.0
Bond	Axial	89.8	124.3	10.0	11.0

* Circumferential

VI. SUMMARY AND CONCLUSIONS

A. Summary

1. Turbine Engine Component Development

The development and evaluation of an improved grade of beryllium was the most significant achievement of this portion of the program. The initial selection of material grades to be evaluated was based upon accumulated experience in attempting to adapt commercial grades of vacuum-hot-pressed beryllium to high-strength forging applications. Commercial grades had been designed for specific uses, compatible with the vacuum-hot-pressing process and product. They were not designed as forging grades. Forging response was generally unsatisfactory and reproducibility was poor.

Evaluation of the materials in this program was aimed at improving cleanliness, reproducibility, and hence, forgeability, as well as strength. The material selected at the conclusion of Phase I demonstrated improved response to all these criteria. Forgeability was generally higher and the range of forgeability response was narrowed considerably. A capability was shown for reproducibly exceeding the 70 Ksi yield strength level without a high degree of work. Through proper selection of the forging parameters and a moderate degree of deformation, a yield strength level exceeding 80 Ksi was demonstrated.

Upscaling material production from laboratory sizes to production blocks was successfully accomplished and provided material for other major development programs, as well as the later phases of this program. The forgeability, as such, was not a major problem, considering the fact that specialized tooling and procedures for forging are required for any grade of beryllium.

Procedures for multidirectionally working beryllium were developed. Although the tooling designed and built under this program was evaluated under a separate program, it performed successfully. This tooling allowed the upset-forging of a four-inch-diameter by 20-inch-long billet, and complemented existing technology on forward-extrusion procedures. Therefore, this portion of the program not only provided material, but tooling and procedures from which the more comprehensive engine component program could proceed.

2. Cone Development

The results of this portion of the program followed a typical pattern for the forging development of a new beryllium geometry. Procedures and tooling must be tried, corrected, and proven before success can be attained, since beryllium's "forgiveness factor" is low. Once operative, however, the forging procedure can be used with good reproducibility as demonstrated during the last series of subscale cone tryouts.

The cone-forming operation itself could be modified for greater economy, but evidence indicates it is the least troublesome of the individual operations performed. Manufacturing the cylinder from which the cone is formed has caused the greatest difficulties. Minor tooling problems caused failure of the first series of back-extrusion operation subscale blanks. Back-extrusion and forward-extrusion operations were both unsuccessful for the full-scale blank. Inadequate restraint is suspected in the case of the back-extrusion, but this condition can be readily modified. Forward-extrusion of a large beryllium cylinder, however, may require a more extensive development effort.

The jacket design was based upon past experience, but the hollow cylindrical extrusion attempted represented a significant size scale-up. Also, the inner diameter of a hollow forward-extrusion is vulnerable to tearing, just as the outer diameter of a back-extrusion is most susceptible to rupturing. Many possibilities exist for correcting jacket failure, among which are material and design changes, as well as forging parameter modifications. The technical difficulties associated with attempts to upscale cone size can be favorably overcome once requirements for conical forgings materialize.

B. Conclusions

The following specific conclusions have been derived from the investigative work conducted during this program.

1. Type 4 beryllium made from minus 20 micron virgin powder demonstrated superior response to forging and improved mechanical properties when compared to the other grades of beryllium investigated.

2. The forgeability of all four grades of beryllium decreased with increasing temperature in the range from 1350 to 1450°F.

3. Forgeability was not significantly affected by increasing the holding time at a forging temperature of 1400°F from one-half to 2-1/2 hours.

4. The forgeability of the five-inch-diameter by five-inch-high billets compared favorably with the two-inch-diameter by two-inch-high billets for Types 2 and 3 beryllium, and was higher for Types 1 and 4.

5. Forged beryllium cones having height/diameter ratios greater than one can be produced from hollow cylinders by using forming techniques.

6. The use of solid, deformable filler material inside a hollow cylinder improved material utilization during cone-forming by controlling the wall thickness. Both graphite and brass were effective filler materials.

7. A wall thickness of one-half inch is adequate for forming an eight-inch-diameter cone.

8. Open-ended cones can be successfully formed without using forward restraint.

9. Yield strength in excess of 80 Ksi was achieved in two directions for all the cone-forging sequences employed and tested.

10. Room-temperature yield strength was maintained after thermal treatments at temperatures as high as 1500°F.

11. Elongation values depended upon the test direction, the forging sequence, and the test location. Elongation in excess of ten per cent was attained in preferred directions.

12. Cast beryllium was successfully back-extrude at 1800°F using compressive restraint.

13. A three-step (back-extrude, forward-extrude, and form) procedure appears to be a practical method for the manufacture of a thin-walled beryllium cone forging having a height/diameter ratio exceeding three-to-one.

VII. RECOMMENDATIONS

It is recommended that forging be employed for manufacturing beryllium cones for strength-critical applications and that additional time and funds be allocated for final development of the process for specific geometries when they are defined.

Use of this forging process or other processes which require multiple operations involving costly preparations such as jacketing or in-process machining is not recommended for purposes of cost reduction, since it would not be readily attained regardless of the degree of material utilization anticipated.

It is further recommended that a procedure of back-extrusion, forward-extrusion, and forming be used for manufacturing those cones having a height/diameter ratio greater than three-to-one.

APPENDIX

MATERIAL SPECIFICATION, ACCEPTANCE PROCEDURES AND RESULTS, AND PRODUCT TEST EQUIPMENT AND PROCEDURES

APPENDIX

A. MATERIAL SPECIFICATION

The beryllium used for Phases II, III, and IV of this program conformed to Ladish Co. Specification B-102B. The requirements of this specification are listed below.

1. Chemical Composition

Billets to be used for forging shall be made from virgin powder produced from vacuum-melted and cast ingots, and shall meet the following chemical composition limits (chemical analysis to be performed on solid billet samples):

Beryllium Oxide	2.0/4.25 per cent
Carbon	1500 parts per million (ppm) maximum
Manganese	350 ppm maximum
Aluminum	850 ppm maximum
Titanium	400 ppm maximum
Silicon	500 ppm maximum
Chromium	200 ppm maximum
Iron	2000 ppm maximum
Nickel	300 ppm maximum
Magnesium	500 ppm maximum
Calcium	100 ppm maximum
Copper	150 ppm maximum
Zinc	100 ppm maximum
Molybdenum	10 ppm maximum
Lead	10 ppm maximum

2. Grain Size

The particle size of the powder used to vacuum hot press the billet shall be 98 per cent less than 20 microns.

3. Density

Water displacement density shall exceed 99 per cent of theoretical, with appropriate correction for the beryllium oxide content.

4. Inclusion Size

Maximum allowable inclusions shall have an average size of 0.030 inch maximum. The combined volume of inclusions shall not exceed the volume of a 0.030-inch sphere per cubic inch of beryllium.

5. Soundness

Vacuum hot pressed block used for forging will be ultrasonically inspected according to Specification AMS-2630. Indications of over approximately 0.035 inch will be reported as to number and location.

6. Mechanical Properties

The minimum acceptable room-temperature mechanical properties of the vacuum hot pressed block shall be:

Ultimate Tensile Strength . . . . 55 Ksi
Yield Strength (0.2 per cent offset) . . . 45 Ksi
Elongation . . . . 1 per cent

B. MATERIAL ACCEPTANCE PROCEDURES AND RESULTS

Prior to accepting material purchased for forging use, beryllium is subjected to the following non-destructive inspections to ensure aircraft-quality material free from detectable flaws and defects which might have a detrimental effect upon the processing or performance of the completed part. Surface discontinuities and porosity are readily revealed using dye-penetrant and macro-etch inspection techniques. Ultrasonic inspection methods allow detection of internal cracks, voids, and discontinuities with a high degree of confidence. Radiographic tests are most useful in detecting high-density particles within the billet. The ability to resolve inclusions of small size diminishes with increasing billet size, but this technique, when used in conjunction with the foregoing tests, allows confidence in the material integrity.

1. Ultrasonic Inspection

Equipment . . . . . Curtiss-Wright Immerscope, Model No. 424D
Crystal . . . . . . Lithium sulfate, 0.375-inch diameter
Frequency . . . . . 15 megacycles
Couplant . . . . . Water, two-inch path distance
Procedure . . . . . Sensitivity is calibrated for an oscilloscope peak height of 75 per cent of the surface wave using a two-inch diameter by 1-1/2-inch high beryllium standard. This standard has a flat-bottomed, 0.047-inch diameter hole 0.75 inch deep (conforms to ASTM E127-61T, Series A). Longitudinal and shear-wave forms are used to inspect the material.

2. Radiographic Inspection

Equipment	Philips-Norelco, Model No. MG100, Constant Potential X-Ray Tube with a one-millimeter beryllium window and 1.5-millimeter focal spot
Film	Kodak Type M Ready-Pack, processed automatically
Penetrameters . . .	Beryllium in 0.125-inch increments to one inch, 0.25-inch increments from one to 2-1/2 inches, plus four, six, and eight-inch sizes (conform to MIL-STD-271D)
Procedure	Billets are exposed using a constant milliampere-second line calibration curve as a guide. A focal distance of 60 inches is used. Due to the transparency of beryllium, sensitivities of one per cent or better are possible to six-inch-thick sections (0.060-inch diameter inclusions are detectable in six-inch-thick sections). Sections from six to 8-1/4 inches thick have been radiographed to between one and two per cent sensitivity level reproducibly.

3. Dye-Penetrant Inspection

Procedure	Inspect in accordance with Specification MIL-STD-271D.

4. Macroetch Inspection

Procedure	The billet is submerged in a five-percent-by-volume sulfuric acid in water solution for 20 to 30 minutes. The billet is then rinsed in water and air-blast dried. This technique reveals striations and heterogeneities resulting from chemical segregation or density variations. In addition, machining marks and possible surface damage are removed during this treatment.

5. Forgeability Testing

The forgeability test consists essentially of upset-forging a representative sample of beryllium and determining the percentage of material yield after removal of defects. The standard specimen is a two-inch diameter by two-inch high cylinder having a 3/16-inch radius on the top and bottom edges. The specimens should have a machined surface of 64 RMS or better, and be etched in a six per cent sulfuric acid solution to remove approximately 0.003 inch from all surfaces. The forgeability billet is heated to 1400°F and held at this temperature for one-half hour prior to forging. The billet is then forged to a height reduction of 60 per cent (0.8 inch) between flat dies which are preheated to 800°F±50°. A graphite-in-oil type die lubricant is used. After cleaning and weighing, all forging defects are removed by machining in such a manner so as to provide the largest sound cylindrical disc from which a percentage of yield by weight can be calculated. The machined discs are inspected using acid etch and dye-penetrant techniques, and are remachined if necessary to insure removal of defects. The ratio of the weight of the rupture-free disc to the weight of the original billet is the forgeability index.

C. PRODUCT TEST EQUIPMENT AND PROCEDURES

1. Room-Temperature Tensile Tests

a. Equipment:
   Baldwin-Lima-Hamilton BTE Hydraulic Universal Testing Machine

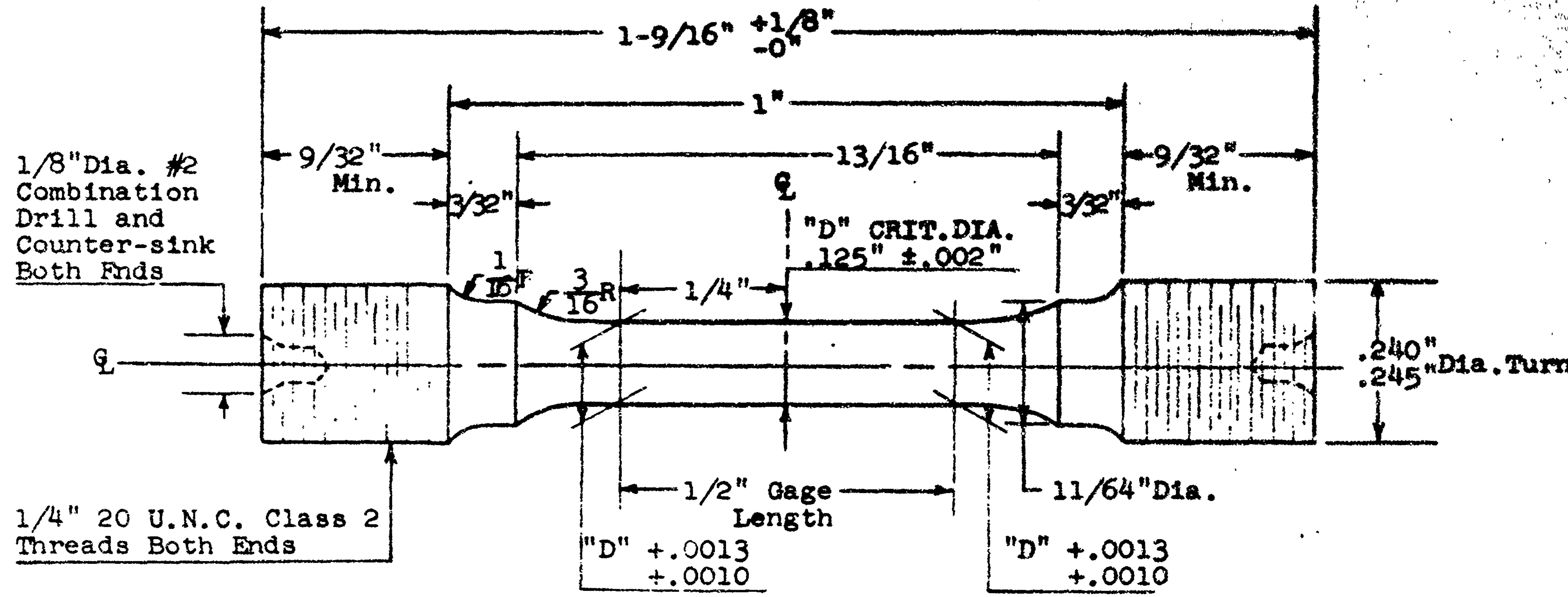
b. Extensometers:
   BLH Microformer

c. Strain Rate:
   0.005 inch/inch/minute to fracture

d. Test Specimen Configuration:
   Modified ASTM E8, shown in Figure 93

e. Test Specimen Preparation Tools:
   1) Cutting Tools - Roughing: Carboloy 883BR12; Side Angle: 23°; Front Angle: 45°; Back Rake: 4° positive; Shank Clearance Angle: 20°; Rough Carbide Clearance Angle: 15°; Finish grind to 10° on diamond wheel with 0.005-0.010 inch radius.
   2) Threading Tools - Single-point 60° included angle, clearance and material as above. Hand hone to 0.005-inch radius for 0.125-inch diameter specimens; 0.005-0.007-inch diameter specimens.
   3) Cut-in and Semi-cut Tools - 883 carbide tip, clearance as above. Round-nosed tool offset 30°; tip offset 30° to centerline of shank.

f. Test Specimen Preparation:
   1) Saw-cut blanks.
   2) Center drill, using C-2 for 0.125-inch diameter specimens, E-2 for 0.250-inch diameter specimens.
   3) Rough machine using live center. Speed 350-400 rpm, feed 0.001-0.003. Depth of cut not to exceed 0.100. Turn to 5/16-inch diameter for 0.125-inch diameter specimens.
   4) Face to length and re-center.



NOTES: 0.001" Maximum eccentricity on all diameters and threads.
0.0005" Maximum out-of-round on gage diameter.
8 RMS (Maximum) longitudinal polish on gage diameter and tangent radii.
Gage length tapered to center from both ends.
Allow 0.002" Minimum-0.003" Maximum on critical diameter for chemical polish.

FIGURE 93

DIAGRAM OF 0.125-INCH DIAMETER BERYLLIUM TENSILE TEST SPECIMEN
(DRAWING NOT SCALED)

5) Finish machine to thread size using dead center. Feed 0.001-0.003, speed 400 rpm. Two passes, second pass not to exceed 0.005 depth of cut.
6) Cut to size in shoulder section using dead center. Feed 0.001-0.003, speed 400 rpm. Two passes at 0.030 depth of cut and one clean-up pass.
7) Chamfer ends approximately 1/64 inch mechanically on belt grinder.
8) Thread 1/4 20-WC for 0.125-inch specimens; 1/2 13-WC for 0.250-inch specimens. Use dead center, 100-150 rpm speed. Depth of cut for two passes 0.010, then 0.005 depth of cut per pass until within 0.008 of size; two passes 0.003, one 0.002 pass, and one clean-up pass.
9) Rough cut in reduced section to 0.020 oversize using live center. One 0.015 pass, one 0.010 pass (on 0.125-inch specimens). Feed 0.001-0.002 and 400 rpm speed.
10) Clean center holes mechanically with center drill.
11) Machine reduced section to 0.005 oversize using live center. One pass (on 0.125-inch specimens) at 0.002-0.003 feed and 400 rpm speed. Change to dead center for one 0.005 pass, one free pass at 0.001 feed and 400 rpm speed.
12) Polish circumferentially between live centers mechanically at 3000 rpm speed using No. 320 grit emery cloth.
13) Polish longitudinally between live centers mechanically at five to seven rpm speed using Nos. 320, 400, and 600 grit emery cloths.
14) Finish per Ladish Co. procedure for electro-polishing beryllium test specimens as follows:
    a) Bath Composition - 82 volume per cent concentrated phosphoric acid; 18 volume per cent distilled water; 218 grams chromium trioxide per liter of liquid.
    b) Procedure - Specimens are polished mechanically in both longitudinal and transverse directions using Nos. 320, 400, and 600 grit emery cloths. Specimens are then placed as the anode in a 120°F bath. Current density of approximately 20 amperes per square inch is maintained for 1-1/2 to two minutes. The specimens are then clamped from the opposite ends to obtain uniform action, and the process is repeated. The bath temperature, time, and current density are variable over a wide range and some experimentation may be necessary to achieve the desired finish for each type of beryllium. Approximately 0.001 inch per minute is removed, resulting in a smooth, bright, finish free of pits and mechanical polishing marks. A satin finish is often obtained in lots of beryllium which have a high oxide content. This can be overcome by increasing the current density and shortening the immersion time. If severe pitting is encountered, lowering the bath temperature is in order.

2. Basal Plane Orientation Determinations

a. **Equipment:**

The equipment consists of a General Electric XRD-3 Diffraction Unit, and S.P.G. Single Crystal Orientor, and a Leeds & Northrup Model "S" Speedomax Indicating Recorder. Figure 94 illustrates the general arrangement of the equipment.

b. **Equipment Setup:**

An unfiltered CuK_{α} radiation is produced by a CA-7 Coolidge X-ray Diffraction Tube with 50 KVP and 16 milliamperes direct current applied. A No. 2 (one-millimeter diameter) beam collimator and open detector beam tunnel (shutters removed), a 0.3-degree detector slit, and a nickel filter are used in conjunction with the Single Crystal Orientor. (A 0.3-degree detector slit is used in place of the shutters on the beam tunnel. The shutters were removed because vibrations caused variations of the aperture.) The diffracted X-rays are detected by a Geiger-Mueller Counting Tube, Victoreen Thyrode Type 1389. The No. 1 Tube has an argon atmosphere and a 0.030-inch thick beryllium window. The tube is operated as a proportional counter.

c. **Procedure:**

A modified Jetter and Borie[10] technique was used to develop the pole figures. The spherical specimen (shown in Figure 95) is rotated about the pedestal axis at 1/18 rpm by a direct-drive, synchronous motor. The angle of inclination is manually adjusted in 18-degree increments for each 360 degrees of rotation. The two-theta angle was adjusted for maximum intensity in the vicinity of 50.9 degrees for the basal (0001) plane. The intensity variations were recorded on a chart moving at one inch per minute.

d. Determination of Random Orientation:

The initial random orientation specimen was sectioned from a vacuum hot pressed billet of Type 2 beryllium, Heat No. 3481. The random level was determined by the average intensity of the plane normal to the pressing direction. This permitted comparison of the random orientation level to all previous random levels used at Ladish Co.

The random orientation level for B-102B, minus 20 micron beryllium, was determined by averaging the intensity levels at each ten degrees of rotation at each ten degrees of inclination. Out of three heats checked, the most random was Heat No. 3846. Random intensity of 410 cycles per second was used on this program.

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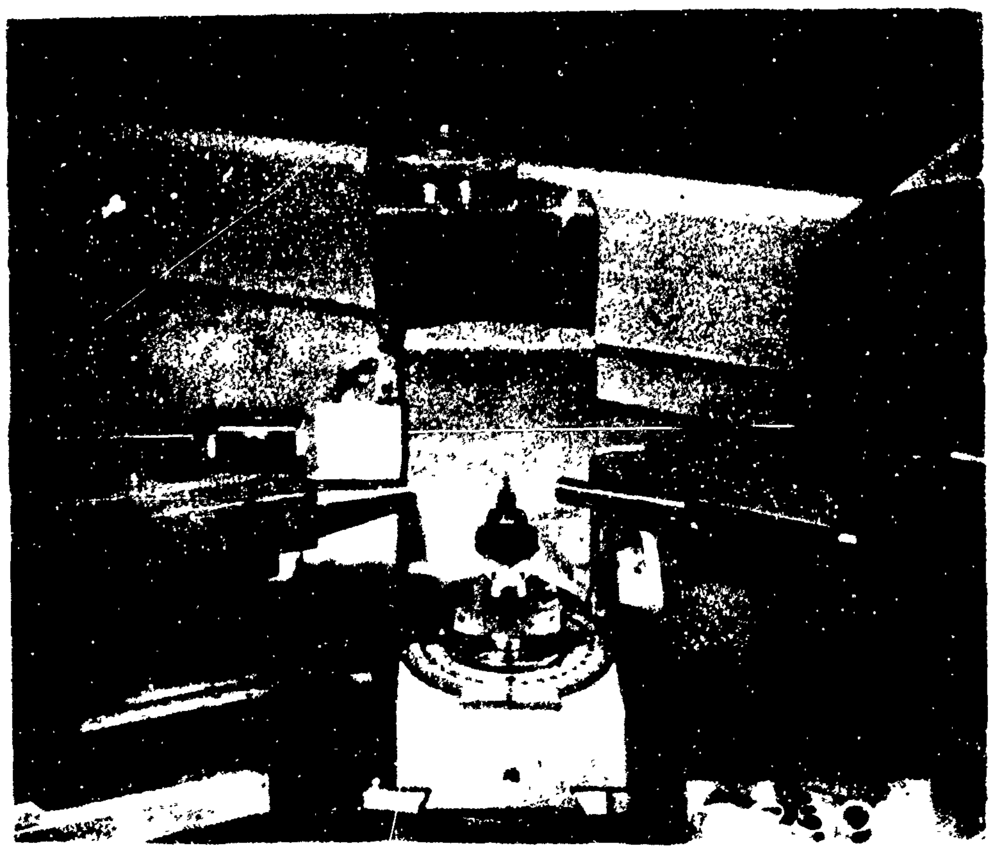
10 "Effects of Thermo-Mechanical Variables on the Texture and Bend Ductility of High-Purity Beryllium Sheet;" The Franklin Institute; May 15, 1964; Contract AF33(657)-11234, pp. 19-35

GENERAL VIEW



DETAIL SHOWING SPHERICAL SPECIMEN IN SINGLE CRYSTAL ORIENTOR

FIGURE 94

EQUIPMENT AND SETUP OF X-RAY DIFFRACTION UNIT FOR BERYLLIUM BASAL PLANE POLE FIGURE DETERMINATIONS

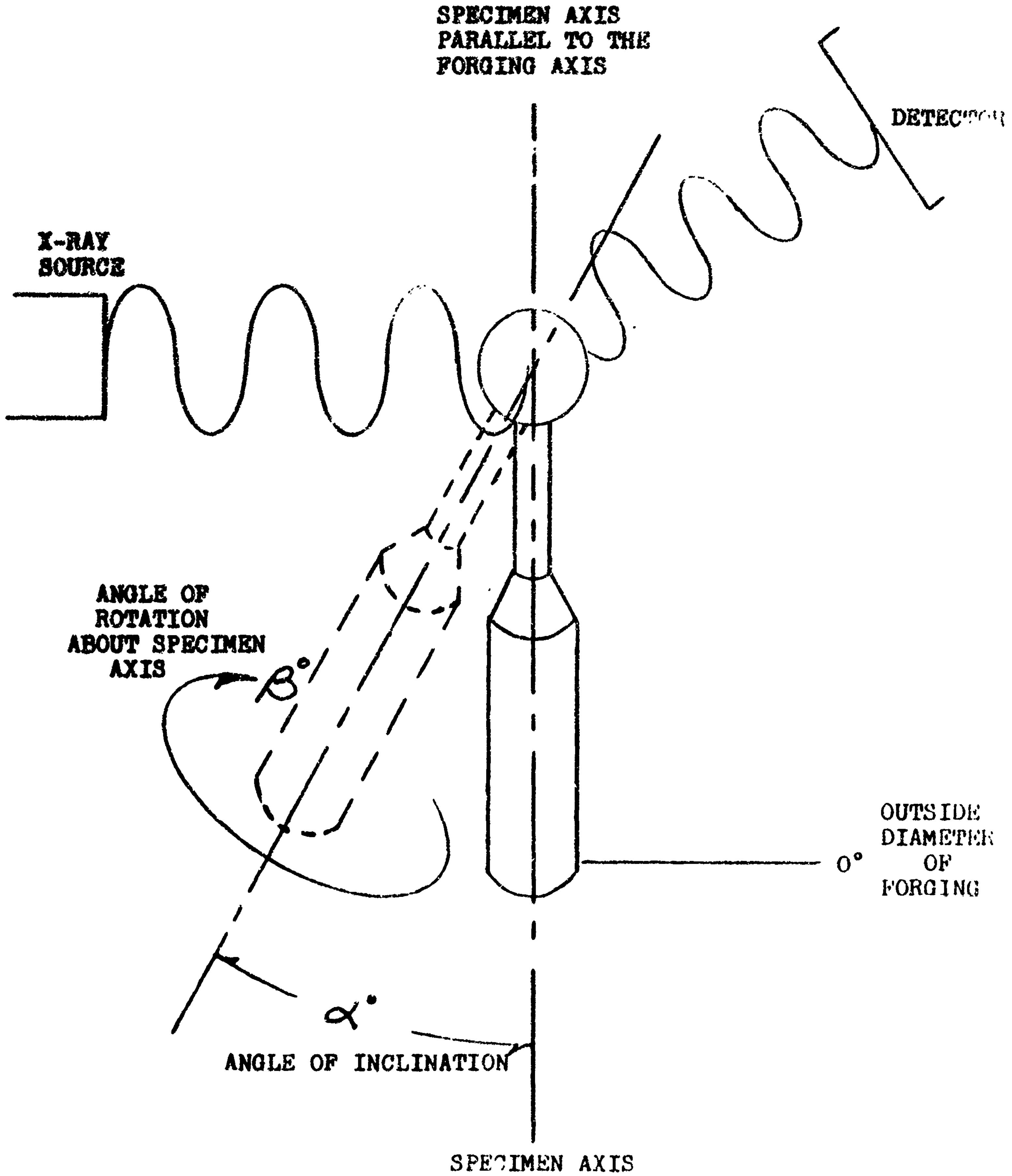


FIGURE 95

SCHEMATIC OF POLE FIGURE SPECIMEN
(SPHERE IS 0.060-INCH DIAMETER)

3. Metallographic Analyses

a. Equipment:
Carl Zeiss Ultraphot II Research Microscope (shown in Figure 96) using 40X oil-immersion AUFL polarizing objective and mercury light source

b. Test Specimen Preparation:
1) Mount in "Koldmount" epoxy resin.
2) Place in "Automet" holder; grind flat on No. 80 grit belt.
3) Polish through Nos. 120, 240, 400, and 600 papers wet using heavy pressure and "fast" speed on the Automet. Rinse between each paper, using ultrasonic cleaner.
4) Finely polish as follows -
a) No. 9 diamond on canvas cloth (five minutes).
b) No. 6 diamond on nylon cloth (five minutes).
c) No. 3 diamond on nylon cloth (five minutes).
d) No. 1 diamond on Duracloth (five minutes).
e) Linde "B" and water on microcloth (twenty minutes).

c. Etching Procedure: This procedure is used for electron microscopy replication.
1) Electrolyte - 450 cc. absolute methanol (CH_3OH)
150 cc. copper nitrate ($Cu(NO_3)_2$)
250 cc. glycerine
5 cc. hydrochloric acid (HCl)
2) Electrolytically etch as follows:
a) Use Disa Electropol Mark 5
b) Setting "polish"
c) Five seconds time
d) Flow rate "6"
e) Adjust the current to 1.5 amperes on 100-mm.^{2} sample (0.015 ampere/mm.^{2}).

Note: The etching time can be varied to compensate for materials of different compositions.

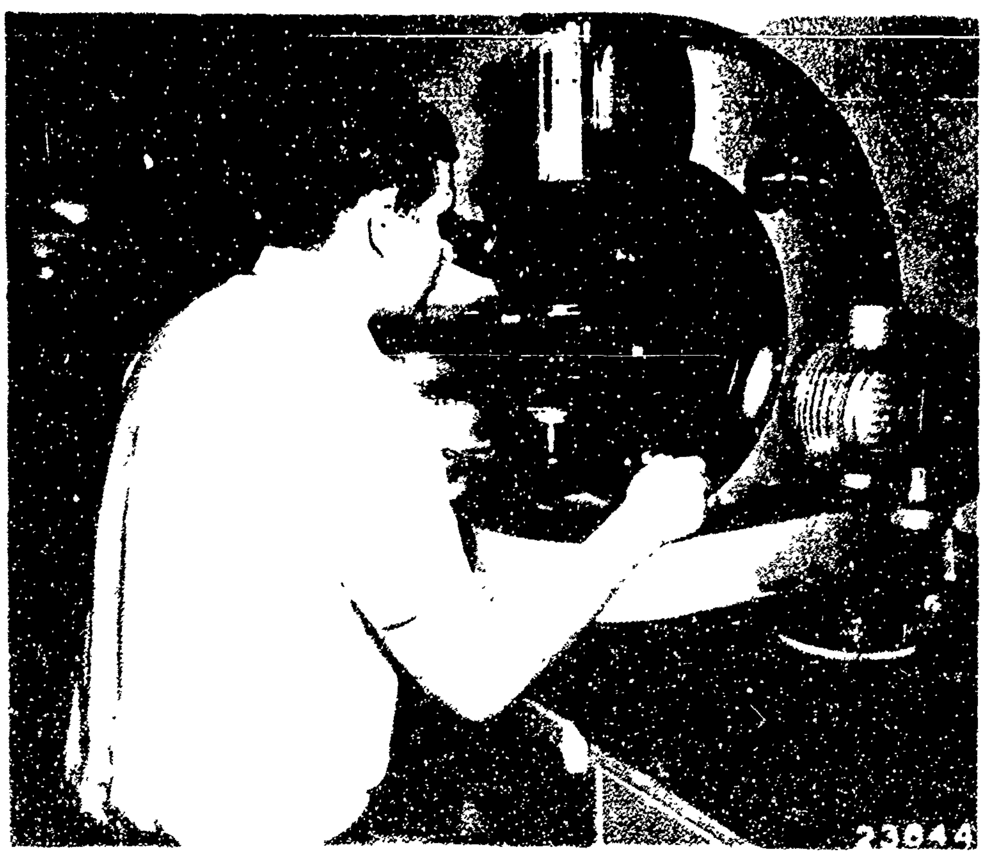


FIGURE 96

ZEISS ULTRAPHOT II
RESEARCH METALLOGRAPH

REFERENCES

1 Hayes, A. F. and Yoblin, J. A., "Beryllium Forging Program," Contract AF33(600)-36795 with the U.S. Air Force, WPAFB-MTL Report ASD TR-62-7-647, Ladish Co., June 1962

2 Williams, R.F. and Ingels, S.E., The Fabrication of Beryllium Alloys - Volume II: "Forming Techniques for Beryllium Alloys," NASA TMX-53453, July 1966

3 Cken, S. and Kilks, B. H., "Structural Evaluation of Beryllium Solar Panel Spars," AFFDL Technical Report TR-65-45, The Boeing Company, August 1966

4 Barnett, F.E., Finn, J.M., and Koch, L.C., "Beryllium Structures for Aircraft," Paper No. 660666 presented at the SAE Aeronautic & Space Engineering and Manufacturing Meeting, Los Angeles, California, October 3 through 7, 1966

5 Kosinski, E. J. and Noel, R. J., "Development of Beryllium Forging Techniques for Turbine Engine Components," Interim Engineering Report No. III, Contract AF33(615)-2231, MM Project No. 8-329, Ladish Co., 15 July 1966

6 Kosinski and Noel

7 Kosinski and Noel

8 Frankeny, J.L. and Floyd, D.R., "Ingot Sheet Beryllium Fabrication," Dow Chemical Company Report on Contract AT(29-1)-1106, February 9, 1968

9 Hayes, A.F., "Beryllium Forgings for Turbine Engine Components," Technical Report AFML-TR-67-334, Ladish Co. under Contract AF33(615)-2231, October 1967

10 "Effects of Thermo-Mechanical Variables on the Texture and Bend Ductility of High-Purity Beryllium Sheet," The Franklin Institute, May 15, 1964, Contract AF33(657)-11234, pp. 19-35

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13. ABSTRACT

This manufacturing program, originally initiated for forging beryllium jet engine blades and discs and later redirected to beryllium cones, established an improved beryllium forging grade and a practical forging sequence for the manufacture of cones having height/diameter ratios greater than 1.5-to-one and nominal yield strength of 75 Ksi. Of the four types of beryllium selected for evaluation during Phase I, the grade hot-pressed from minus 20 micron virgin powder reproducibly demonstrated superior forgeability and mechanical properties. All grades showed higher forgeability at 1300-1350°F versus 1350-1450°F. Material, tooling, and technical development for the blade forgings were transferred to a similar, more comprehensive, beryllium engine program.

A series of cones 8-1/4-inch major diameter was produced and evaluated during Phase III by a basic manufacturing process consisting of forging a conical frustum from a hollow cylinder. Expendable hot filler material such as graphite or brass were used to prevent buckling and to optimize the material utilization. A different deformation processing sequence was used on each cylindrical cone blank to produce various textures and a range of mechanical property values for future selection of the most economical process capable of meeting specific requirements. Forging defects developed during extrusion of the hollow cylinders so that an adequate evaluation of the forming process was not possible in Phase III. Tensile data showed yield strengths from 78 to 96 Ksi and ultimate strengths from 90 to 123 Ksi for circumferential and axial test directions. Tensile elongation varied considerably, depending upon forging sequence and testing location and direction.

The program was modified to provide additional subscale trials and to change configuration of the full-scale cone to more closely approximate future requirements. These trials were directed toward defining parameters such as the degree of restraint and evaluating methods of maintaining geometry control. The conical frustums formed successfully, showing that open-ended cylinders can be formed without using forward restraint. Both graphite and brass fillers effectively maintained wall thickness. The procedure for manufacturing the full-scale cone entailed back-extrusion, forward-extrusion, and forming. Rupturing occurred during both extrusion operations and prevented progressing to the forming operation. Additional trials should correct these technical difficulties and enable the production of forged beryllium cones in the size range of 14-inch-diameter by 48 inches high having nominal yield strength of 75 Ksi.

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Hydrodynamic Restraint						
Hydrostatic Compressive Restraint						
Upset Forging						
Forward Extrusion						
Back Extrusion						
Forming						
Expendable Filler Material						
Conical Configurations						
Preforms						
Structural Shapes						
Vacuum-hot-pressed beryllium						
Arc-cast beryllium						
Mechanical Properties						
Crystallographic Orientation						
Basal Plane Orientation						
Preferred Orientation						
Random Orientation						
Microstructure						
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Pole-figure Studies						
Model Studies						
Hollow Cylindrical Shapes						